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Utility Test Results of a 2-Megawatt, 10-Second Reserve-Power System

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Abstract

This report documents the 1996 evaluation by Pacific Gas and Electric Company of an advanced reserve-power system capable of supporting 2 MW of load for 10 seconds. The system, developed under a DOE Cooperative Agreement with AC Battery Corporation of East Troy, Wisconsin, contains battery storage that enables industrial facilities to "ride through" momentary outages. The evaluation consisted of tests of system performance using a wide variety of load types and operating conditions. The tests, which included simulated utility outages and voltage sags, demonstrated that the system could provide continuous power during utility outages and other disturbances and that it was compatible with a variety of load types found at industrial customer sites.

Acknowledgments

Sandia National Laboratories would like to thank Dr. Imre Gyuk of the U.S. Department of Energy, Office of Power Technologies within the Office of Energy Efficiency and Renewable Energy, for support and funding of this work.

Contents

Executive Summary **ES-1**

1. Overview **1-1**
Background and Rationale 1-1
Summary of Tests 1-2
Test Site 1-2
Installation and Test Setup 1-4
Grid Synchronization/Standby and Light-Load Tests 1-4

2. Partial-Load Tests **2-1**
Introduction 2-1
Passive Resistive and Reactive Load 2-1
Loss of Utility, Full Duration 2-1
Loss-of-Utility Test 2-2
90% Voltage Sag 2-2
Unbalanced Load and Sag Tests 2-4
Operation with Partial Capacity 2-4
Repetitive Discharge Tests 2-5
Resistive and Capacitive Load 2-6
Capacitor Switching Test 2-6
Loss-of-Utility Test 2-7
Repetitive Discharge Tests 2-8
Resistive and Rotating Machine Load 2-8
Loss-of-Utility Test 2-8
Motor Starting 2-11
Repetitive Discharge Tests 2-11
ASD, Resistive and Single-Phase Electronic Loads 2-11
ASD Outage Tests 2-12
90% Voltage Sag Test 2-12
Repetitive Discharge Tests 2-14
Electronic Load Outage and Sag Tests 2-14

3. Full-Load Tests **3-1**
Ten-Second Tests 3-1
Short-Duration Tests 3-1

4. System Design and Operation Implications from Test Results **4-1**
System Design Ratings 4-1
Reconnection Logic 4-2
Switch Commutation Impacts 4-4
Synchronizing with Utility/ Oscillations 4-4
Frequency Detection 4-5
Energy Loss Savings 4-5
Energy Management/Power Quality Multimode Operation 4-6
Energy Storage Technology 4-7

5. Conclusions and Further Research **5-1**
Diesel Integration 5-1
Medium-Voltage Interconnection 5-1
Alternative Storage Technologies 5-1
Parallel Generation 5-2

6. References **6-1**

Appendix A: Outage Mitigation Alternatives **A-1**

Appendix B: Detailed List of PQ2000 Prototype Tests **B-1**

Appendix C: List of Tests **C-1**

Figures

Figure ES-1. Test Facility Layout. ES-2
Figure ES-2. Load Transfer upon Loss of Utility Source. ES-2
Figure ES-3. Restoration of Utility after Outage. ES-3
Figure 1-1. MGTF Circuit Diagram with PQ2000 in Full-Load Position. 1-3
Figure 2-1. Partial-Load Test Configuration. 2-1
Figure 2-2. 10-sec Test: System Voltage and Current Traces at Transfer. 2-3
Figure 2-3. 10-sec Test: System Voltage and Current Traces During Reconnect. 2-3
Figure 2-4. Sag Test: System Voltage and Current Traces During Transfer. 2-4
Figure 2-5. Fast Sag Test. 2-5
Figure 2-6. Waveform Capture of R-L Test; Resistive Load Dropped at Transfer. 2-6
Figure 2-7. Transfer Created by 12-kV Capacitor Switching on, with No Other Loads. 2-7
Figure 2-8. Capacitor Strike on Loads Served During PQ2000 Discharge. 2-8
Figure 2-9. Transfer with 300-kVAR Capacitive Load. 2-9
Figure 2-10. Transfer with Motor and Resistive Loads. 2-10
Figure 2-11. Utility Reconnection with Motor and Resistive Loads. 2-10
Figure 2-12. Motor Current Oscillations During Resynchronization. 2-10
Figure 2-13. Unloaded Motor Starting During Discharge. 2-11
Figure 2-14. Current Drop upon Loss of One of the Two ASD Power Supplies. 2-13
Figure 2-15. Transfer with ASD Load Only. 2-13
Figure 2-16. Utility Reconnect with ASD Load Only. 2-13
Figure 2-17. Load Current Oscillations During Utility Resynchronization Stage. 2-14
Figure 2-18. Transfer with Electronic Loads and 25-kW Resistor. 2-15
Figure 3-1. Test Configuration for 2-MVA Load Testing. 3-2
Figure 3-2. Failed Reconnect Attempt. 3-2
Figure 3-3. Transfer During 2-MW, 10-sec Outage Test. 3-3
Figure 3-4. Utility Reconnect During 2-MW, 10-sec Outage Test. 3-4
Figure 4-1. Out-of-Phase Reclose on Decaying Motor Load. 4-3
Figure 4-2. Motor Current Oscillations. 4-4

Tables

Table ES-1. List of System Tests ES-1
Table 1-1. Summary of PQ2000 Prototype Tests* 1-2
Table 1-2. Test Facility Breaker Assignments 1-3
Table 1-3. Auxiliary Load Measurements 1-5
Table 2-1. Full-Duration Discharge; 500-kVA Resistive and Inductive Loads 2-2
Table 2-2. Ten-Second Outage; 500-kVA Resistive/Inductive Loads 2-2
Table 2-3. Voltage Sag Test With Nominal 500-kVA R/L Load 2-4
Table 2-4. Capacitor Strike Tests 2-7
Table 2-5. Loss-of-Utility Tests with Resistive/Capacitive Loads 2-8
Table 2-6. Loss-of-Utility Tests Serving Motor Loads 2-9
Table 2-7. Summary of Outage Tests with ASD Loads 2-12
Table 3-1. Summary of Full-Power, 10-Sec Outage Tests 3-3
Table 3-2. Summary of Results from 30 Short-Duration Discharges at Full Load 3-5
Table 4-1. Utility Reconnection Schemes for Energy Storage Systems 4-2
Table 4-2. UPS Energy Loss Processes 4-5
Table 4-3. Energy Loss Assumptions 4-5
Table 4-4. Sample Energy Loss Calculation for 1-MW UPS 4-6

Acronyms

ASD	adjustable speed drive
DOE	Department of Energy
ESS	Energy Storage Systems
HVAC	heating, ventilation, and air conditioning
MGTF	Modular Generation Test Facility
ms	milliseconds
MVA	mega volt-amp
MW	megawatt
PCS	power conditioning system
PG&E	Pacific Gas and Electric Company
PS	power supply
R/L	resistive/inductive load
RMS	root mean square
SCR	silicon controlled retifier
SMES	superconducting magnetic energy storage
SNL	Sandia National Laboratories
SOC	state-of-charge
UPS	uninterruptible power supply
VAC	volts alternating current
VAR	volt-amp reactive

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Executive Summary

An advanced "off-line" reserve-power system capable of supporting 2 MW of load for 10 secs was evaluated in 1996 by Pacific Gas and Electric Company at its test facility in San Ramon, California. The project was supported by the U.S. Department of Energy (DOE) Energy Storage Systems (ESS) Program under a contract from Sandia National Laboratories (SNL). The system was developed under a DOE Cooperative Agreement with AC Battery Corporation of East Troy, Wisconsin.

The system featured a container housing 384 low-maintenance, lead-acid batteries; a high-speed static transfer switch; and control circuitry, which enabled it to detect utility source disturbances and isolate and support critical customer electric loads. It enabled mission-critical loads at industrial facilities to "ride through" momentary outages.

Novel design elements included:

- Short-term component ratings, enabling the system to be designed for a much lower cost than a system designed for comparable loads at continuous duty;
- A sophisticated monitoring feature that triggered operation during utility-voltage sags, swells, transients, and outages;
- High-speed transfer capability, enabling the system to isolate loads and ramp to full power within one-quarter cycle (4 milliseconds);
- Control circuitry that provided resynchronization with the utility grid once restored to normal;
- A monitoring computer, which reported detailed status and diagnostic information.

Testing was intended to demonstrate system performance using a wide variety of load types and operating conditions that would be found at customer sites in the field. These tests, summarized in Table ES-1, included operation at partial load and full load, and included simulated utility outages and voltage sags.

As shown in Figure ES-1, the facility provided for testing with resistive, reactive, rotating, capacitive, and electronic loads.

A typical load transfer is shown in Figure ES-2. The second trace shows the utility voltage dropping to zero – a simulation of a utility outage caused by opening a line-side breaker (identified as Breaker 52-20). The third trace shows that voltage at the load is supplied by the system after the utility is lost, and that only a minor change in the waveform at the moment of transfer is observed. The fourth and fifth traces represent utility- and load-side current waveforms, respectively. Figure ES-3 shows the corresponding waveforms as the utility is restored (by closing Breaker 52-20, thus simulating the return of utility power).

Table ES-1. List of System Tests

Test	Dates, 1996	Tests
1	April 15-24	Installation, interconnection and protection
2	April 24-25	Grid synchronization/standby and no-load tests
3	June 6-July 29	Partial-load tests (500 kVA)
3.1		Passive-resistive and reactive loads
3.2		Resistive and capacitive loads
3.3		Resistive and rotating machine loads
3.4		Adjustable speed drive (ASD), resistive, and various single-phase and electronic loads
4	August 6-21	Full-load tests (2 MVA)
4.1		Ten-second tests
4.2		Short-duration tests

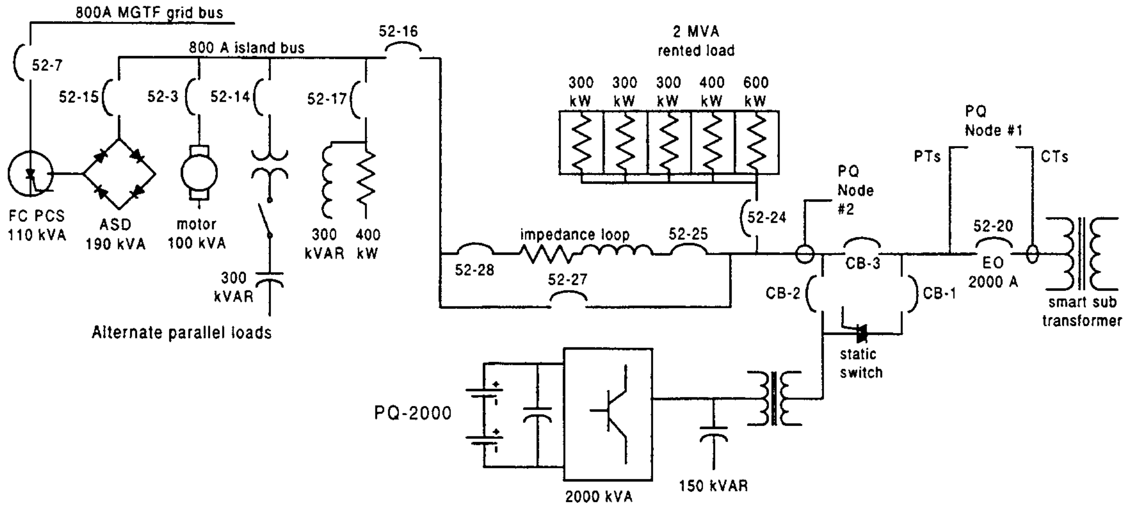

Figure ES-1. Test Facility Layout.

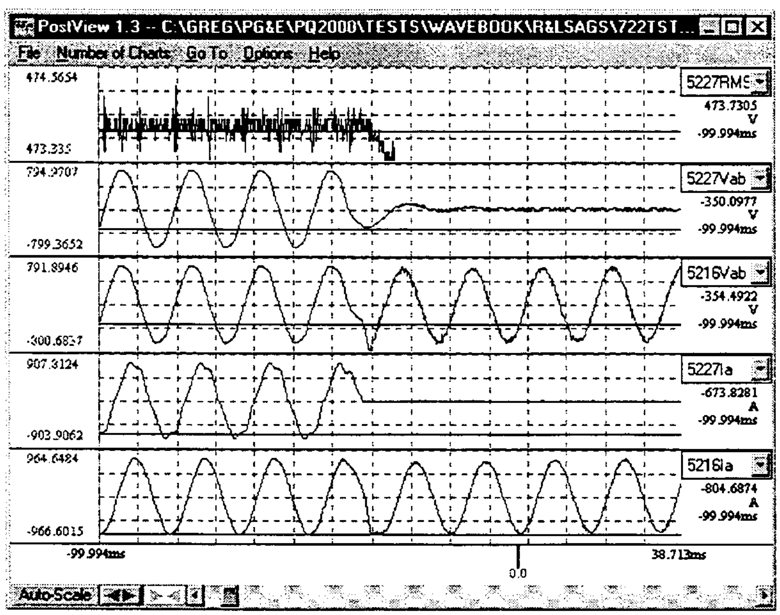

Figure ES-2. Load Transfer upon Loss of Utility Source.

The testing demonstrated that the system could be used to provide continuity of power during momentary utility outages and other disturbances, and that it was compatible with a variety of load types found at industrial customer sites.

A number of lessons were learned with respect to the design and application of off-line reserve-power systems that utilize energy storage. Some of the issues that were identified led to on-site design modifications of the prototype itself, some led to improved designs for subsequent generations of the PQ2000, and some remain for the marketplace to resolve. The issues include:

- *System Design Ratings.* The optimal unit size ratings (in both power and time) remain elusive. Performance ratings are somewhat conservative because the field experience is still limited. True ratings would couple power and time (MW-seconds) because the design constraints are largely driven by component heating.
- *Reconnection Logic.* While the testing demonstrated that off-line designs can support momentary outages within the design performance

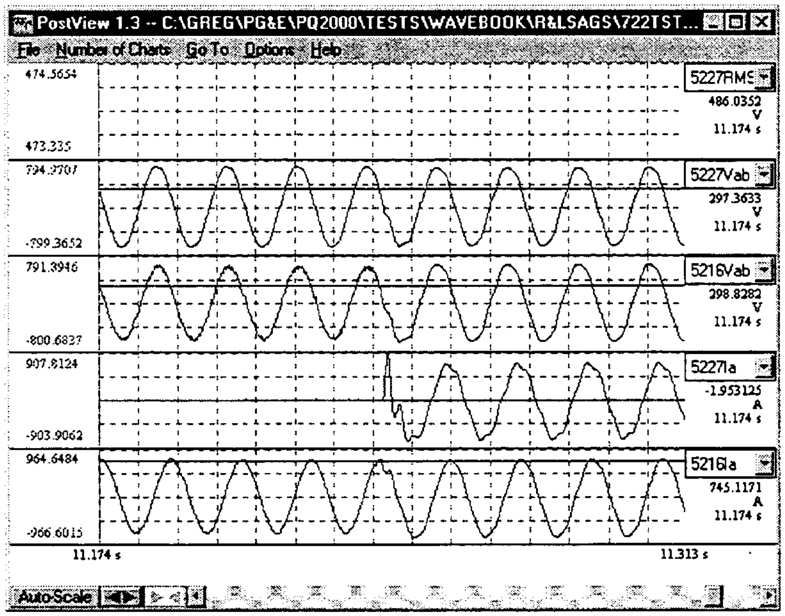

Figure ES-3. Restoration of Utility after Outage.

envelope, it is not clear how the system should respond when the outage is approximately equal to the system temporal rating. For example, if the utility is restored while discharging but it does not have adequate time to resynchronize, should the system transfer the load back to the utility out-of-phase in order to provide continuity of power?

- *Switch Commutation Impacts.* Certain sensitive loads tripped off-line during the transition from the utility source because the transfer scheme requires a momentary overvoltage condition. While the magnitude of the overshoot has been reduced for subsequent designs, the manufacturer and customer should coordinate protection settings as a normal activity during installation to prevent unnecessary loss of load.
- *Synchronizing with Utility/Oscillations.* Some oscillations were observed during the resynchronizing periods before the utility was restored. Such oscillations can generally be expected with loads that react dynamically to supply frequency variations.
- *Frequency Detection.* Under certain conditions, rotating loads were observed to generate back-electromotive force on the load circuit during a utility outage. The presence of voltage initially confounded the utility-monitoring circuitry. To accommodate this situation, frequency detection was added in determining whether protective action is necessary.
- *Energy Loss Savings.* The off-line design approach results in a significant cost savings to the customer by eliminating demand and energy charges associated with rectification and inversion losses. These benefits are estimated to be nearly $300/kW, which is as much as one-third of the total capital cost.
- *Energy Management/Power Quality Multimode Operation.* While combining multiple economic benefits is attractive, various technical and cost hurdles will have to be overcome in a multimode design, particularly in the case of off-line systems, which incorporate short-term component ratings.
- *Energy Storage Technology.* While the system revealed no shortcomings in the battery component, the utility power source industry in general faces enormous challenges with respect to systems requiring longer-term storage. Advanced battery technologies promise greater reliability and consistency for these applications.

A number of follow-on research activities are suggested, given the current stage of power quality technology and the market requirements. These include integration of an off-line system with diesel generation, interconnection at medium voltage (e.g., 12 kV), assessment of alternative storage technologies, and the operation of multiple off-line systems in parallel.

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1. Overview

Background and Rationale

A prototype model of an advanced facility-level backup power system was evaluated during the summer of 1996 by Pacific Gas and Electric Company (PG&E) at its test facility in San Ramon, California (Norris, 1996; and Ball, 1996). The system was designed and manufactured by AC Battery Corporation, and development support was provided by the U.S. Department of Energy (DOE) and Sandia National Laboratories.*

This 2-MW system, given the product designation PQ2000, was derived from an earlier grid-connected battery energy storage system, also manufactured by AC Battery, which was designed to support peaking power requirements on utility distribution systems or customer sites. This previous system housed low-maintenance, lead-acid batteries and power electronics and controls in a modular container, rated at 250 kW and 167 kWh. It was designed for a 480-V, three-phase interconnection.

The PQ2000 utilized most of the mechanical design features of the earlier energy storage system, including the structural housing, internal racking, hydrogen ventilation, cooling, safety alarms, and controls. The new design, however, included a high-speed "static switch" and control circuitry, which enabled it to isolate critical customer electric loads and support them in the event of utility-side power disturbances. The PQ2000 therefore was designed to operate as a voltage source for an isolated load, and had a net system rating of 2000 kVA.

One of the key test objectives of this study was to verify that the PQ2000 could operate as a bridge between the time of the utility outage and the startup of a diesel engine generator. Although the cost of the engine generator and the development of the control integration precluded a comprehensive demonstration of this application, it was reasoned that the most critical aspects would be the operation of the static switch and the capability of the system to maintain its full 2-MW output for the bridging time of about 10 seconds. The prototype was rated for 10 seconds whereas subsequent units were rated at 15 seconds.

* *Final Report on the Development of a 2MW/10 Second Battery Energy Storage System for Power Disturbance Protection.*

Although the prototype was not to be integrated with the diesel, the system did suggest that another niche application exists for power quality devices in a stand-alone technology configuration. The PQ2000 system could be used in applications requiring only short-term (under 10 seconds) protection, and applications where the additional cost of the diesel generator could not be justified. Even in these cases, the 10-second rating exceeded the typical reclosure settings of utility distribution systems, and it was reasoned that about 90 percent of all utility outages could be averted without the added cost of the diesel supplement. Therefore, the PQ2000 in a stand-alone configuration potentially would have application for existing electric customers. The PQ2000 testing would be not only to validate the design ratings, but also to demonstrate the reliability and operation of the unit as a stand-alone technology.

The PQ2000 design promised to take advantage of high short-term component ratings. By understanding its thermal operating characteristics over limited periods, component costs could be reduced. While the original storage system was rated for 250-kW continuous duty, the PQ2000 would be rated for 2,000 kW–eight times the original steady-state rating.

One important goal of the PQ2000 design was the ability to reduce system hardware costs by targeting the short-term duty cycle niche application and eliminating the need for continuous power ratings. Most UPS designs are based on steady-state ratings and can apply power for more than 15 minutes. A 2-MW, 15-minute uninterruptible power supply (UPS) might require the entire basement of a large building, whereas, the PQ2000 could be housed in a standard 20-ft shipping container. In principle, the system could be produced and installed at a significantly lower cost than a standard UPS due to a much smaller volume of battery, the type of short-discharge battery used, and the throughput advantages of using transients ratings for the power train.

The PQ2000 consists of eight battery storage modules within an environmentally enclosed container, a high-speed static transfer switch, and a step-up transformer. The system is capable of sensing a utility voltage or frequency disturbance and switching from standby to full operation in less than four milliseconds. The high-speed transition is intended to eliminate the potential end-user effects of momentary outages, switching transients, voltage sags, and other short-term disturbances to utility power. The PQ2000 utilizes a microprocessor-based controller to supervise aspects of the system operation and is interfaced with a monitoring computer for the user. A monitoring computer reports status and diagnostic information and permits some user control.

This report summarizes the testing and lessons learned from the prototype PQ2000 by PG&E, Innovative Power Systems, and Energy and Environmental Economics, Inc. from April through August of 1996. Key test results from this prototype have been incorporated by the manufacturer in to the second- and third-generation designs, which have since been installed on "mission-critical" loads at customer sites across the country.

Summary of Tests

The overall test objectives were to:

- Ensure that the system met the design specifications of 2 MW and 10 secs;
- Demonstrate the system's performance under the worst-case conditions that could take place at customer sites; and
- Gain installation and operational experience with the system.

Table 1-1 shows a summary of the tests described in this report.

Test Site

Testing was conducted at PG&E's Modular Generation Test Facility (MGTF) in San Ramon, California. An electrical diagram of the test facility (Figure 1-1) shows the location of the prototype PQ2000 (on the low-voltage side of the "Smart Substation" transformer), a 2-MW resistive load (Breaker 52-24), a resistive/reactive load (52-17), an electronic load (52-15), a capacitive load (52-14), and a motor load (shown as the "Gen-Set" on 52-3).

The system's position in this configuration permits full loads of 2 MVA because it is connected on the 1600-Amp smart-sub bus. Another position, labeled in Figure 1-1 as "Alternate PQ2000 Location," is used for partial-load tests and permits the variation of the 480-Vac bus voltage.

The "Impedance Loop" shown in Figure 1-1 is a variable series impedance used to create voltage-sag conditions. In addition to the bus voltage variations, the partial-load tests were designed to evaluate a wide range of load types, as illustrated in the figure. The project did not have the resources to test such a variety at the full 2-MVA capacity.

Table 1-2 lists the MGTF breakers and associated test equipment used during the test program.

Table 1-1. Summary of PQ2000 Prototype Tests*

Test	Dates, 1996	Tests
1	April 15-24	• Installation, interconnection and protection
2	April 24-25	• Grid synchronization/standby and no-load tests
3	June 6-July 29	• Partial-load tests
3.1		– Passive-resistive and reactive loads
3.2		– Resistive and capacitive loads
3.3		– Resistive and rotating machine loads
3.4		– Adjustable speed drive (ASD), resistive, and various single-phase and electronic loads
4	August 6-21	• Full-load tests
4.1		– Ten-second tests
4.2		– Short-duration tests

* A detailed list of the tests that were performed is included in Appendix B.

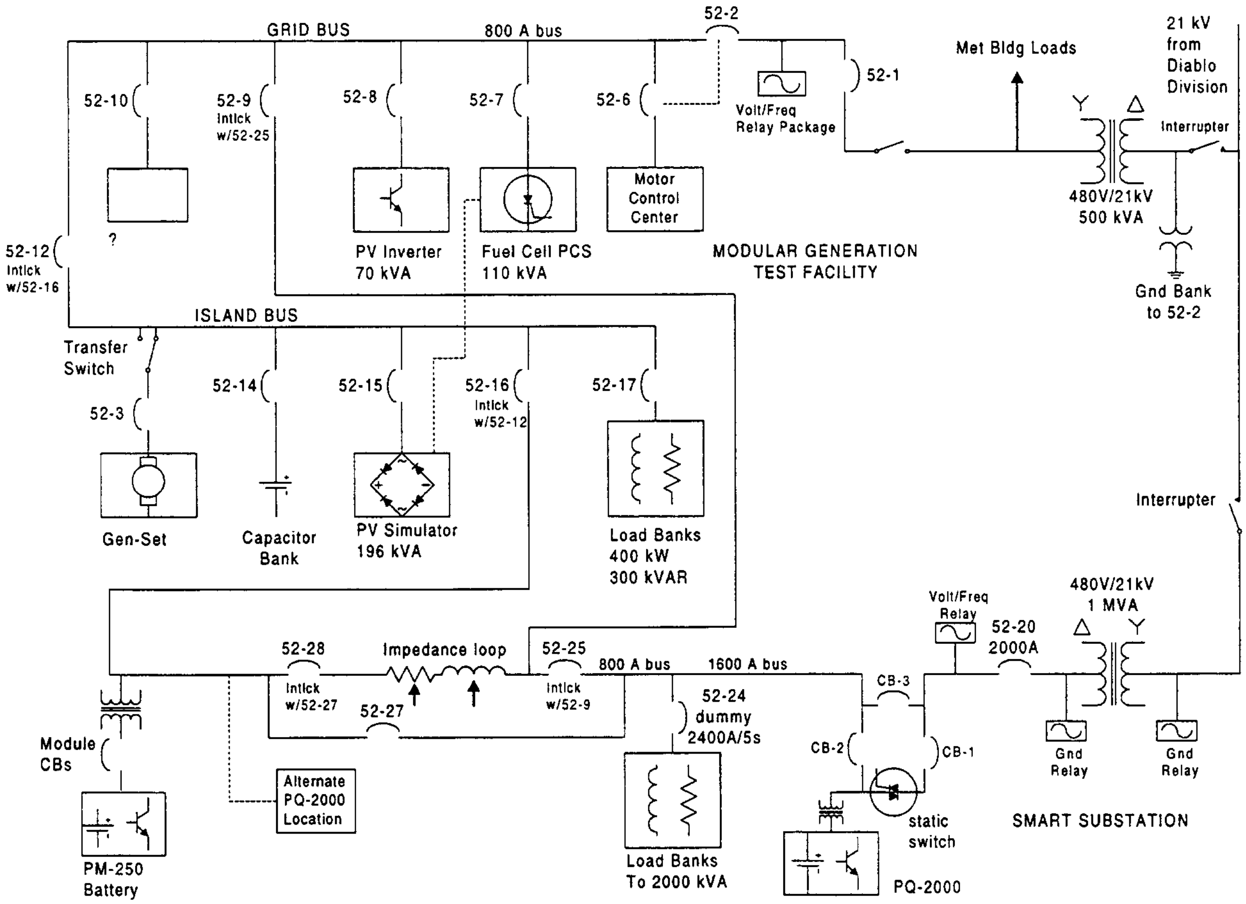

Figure 1-1. MGTF Circuit Diagram with PQ2000 in Full-Load Position.

Table 1-2. Test Facility Breaker Assignments

Breaker	Assignment
52-17	Existing 400-kW — 300-kVAR load banks
52-16	Connection between MGTF and smart-sub bus
52-15	DC simulator (12-pulse ASD-type load)
52-14	Capacitor bank via 12-kV transformer
52-3	Motor generator set and load bank
52-7	Fuel cell inverter
52-20	Main electrical entrance to smart sub
52-24	Dummy breaker (removable shunt bus) serving rented resistive load banks
52-25/52-28	Impedance loop input and output
52-27	Impedance loop bypass

Installation and Test Setup

The PQ2000 was shipped from the manufacturer in East Troy, Wisconsin, using a low air-ride trailer, installed onto a previously prepared foundation, and connected electrically to its test breakers.

The system was inspected to verify that it was in good condition after shipment, that it was properly installed and interconnected with the facility grid, and that it met all of its defined safety and protection requirements. These preparations were performed through April 24, 1996.

1. *Load bank connections.* Five rented load banks totaling nearly 2 MW in resistive load were connected to the output of the system via a dummy breaker (52-24) in the smart-sub switchgear. These loads included three 300-kW banks, one 400-kW, and one 600-kW bank. Additional resistive and inductive loads totaling 500 kVA were provided by facility load banks connected via Breaker 52-17 on the MGTF bus. The connections to these loads, shown in Figure 1-1, were checked and verified by facility personnel.

2. *Remote emergency stop.* A switch was added from the PQ2000 to the control room for emergency shutdown of the system. This provides extra protection for emergency situations in which the utility Breaker 52-20 has been opened, and PQ2000 is to be prevented from operating.

3. *Instrumentation.* High-speed data acquisition instrumentation was connected to measure parameters on both the utility and the load side of the PQ2000 system.

4. *Rotation.* The correct electrical rotation for the facility (A-C-B) was established at the system connection. Measurements showed that the smart-sub 480 Vac rotation was in fact A-B-C, and not A-C-B, indicating that the phases were reversed either at the transformer or at the 21-kV service to the facility. The PQ2000 is designed to be rotation-indifferent because it operates as three independent phase sources. This was verified by running two small discharges with the B-C phases in normal and switched positions.

5. *Hi-pot tests.* Sensitive components were isolated as defined by the manufacturer to facilitate hi-pot tests on the 2000-kVA isolation transformer. The test confirmed that there were no shorts or leakage problems in the transformer or cable insulation between the system and utility.

Grid Synchronization/Standby and Light-Load Tests

The following tests were performed to safely bring individual system components and the complete system to an operational state. These tests were performed and approved from April 24 through 25, 1996:

1. *Safety and protection.* Performed visual inspection, verified safety alarms and control functions, and checked communications (shunt trip, alarms to switchgear, lights, modem operation, etc.).

2. *Static switch communications.* Verified that fiber-optic communications between the battery container and static switch were working properly. The system initially failed this test because a jumper fiber for the backup diesel option was missing, having been lost during the packing or shipping. This fiber was replaced, and a subsequent test verified correct communications.

   Other tests were performed to ensure that the system would fault properly given the loss of one of the seven communication fibers between the static switch and PQ2000 container. All but one occurred without problem. When the *PQ-Run* signal fiber was pulled, the fiber connector was exposed to sunlight, causing the PQ2000 to activate even as the static switch was still gating its switches to the utility. This caused the two voltage sources to exist simultaneously, and a fault current was created from the potential difference. The fault tripped open Breaker 52-27. Shielding the signal fiber resulted in proper fault operation.

3. *Container pre-charge.* Completed two successive and complete equalization charge cycles for all of the eight PQ2000 modules, following procedures defined by the manufacturer.

4. *Static switch synchronization.* Verified the operation of the static switch and container using a light (about 250-kVA) load. Performed a load transfer from the utility to the PQ2000. Tested the synchronization function and ensured that the switch would not close on an unsynchronized utility.

The system passed this test, but the reconnection duration (the elapsed time between the restoration of the utility supply and reconnection of the load to the utility) was recorded for as long as four seconds. The manufacturer noticed a software error related to the counter used to monitor the frequency excursion between the utility and system, and modified the code. This resulted in a significant improvement in the reconnection duration.

5. *Static switch fault detection.* Created a fault on the static switch by manually disabling it. Verified that the PQ2000 set the proper fault on the operator display and sent a fault message to the monitoring computer.

6. *Auxiliary load measurements.* While the static switch and the PQ2000 were synchronized with the utility, and they were supplying a light resistive load, the continuous system power draw to the PQ2000 was measured using a BMI 3030 monitor connected between the PQ2000 and Circuit Breaker 2 (CB-2) of the static switch.

Recordings were made of the container's primary auxiliary loads, which include a heater, two sets of air-conditioners, and a hydrogen blower. These loads are characterized in Table 1-3.

Table 1-3. Auxiliary Load Measurements

Container Status	V	I	kVA Load
No HVAC	201	2.6	0.5
Heater On	200	29	5.8
AC 1 & 3 On	201	19.2	3.9
AC 1, 2, 3 & 4 On	200	35	7.0

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2. Partial-Load Tests

Introduction

The prototype PQ2000 system was tested using a wide variety of load types at partial-load levels (500 kVA maximum). These tests were designed to simulate possible loads and operating modes that could be seen in the field at customer sites. These tests were performed between June 5 and July 29, 1996.

During the course of testing, the manufacturer made certain changes to the design of the voltage detection circuitry, control logic, and other components that were necessary for the system to perform satisfactorily in particular tests. A final series of tests were run after all such changes were implemented, and the test results for this final series are reported here.

In order to characterize the PQ2000's ability to serve a variety of customer loads, the partial load tests were split into four steps, each using a different type of load: (1) passive resistive and reactive load, (2) resistive and capacitive load, (3) resistive and rotating machine load, and (4) a combination of adjustable speed drive (ASD), resistive, and various single-phase and electronic loads.

In addition to load-specific characteristics, the first set of tests covered general aspects of the system's operation, such as recharge and operation with fewer than eight modules.

The PQ2000 was connected at the partial-load-test location detailed in Figure 2-1 for all of the tests described in this section.

Passive Resistive and Reactive Load

These tests were performed using parallel 400-kW and 300-kVAR load banks, totaling 500 kVA and connected on Breaker 52-17 (all other breakers were open during these tests).

Loss of Utility, Full Duration

This test was designed to determine the system response to a loss of utility condition and the maximum discharge duration given an indefinite outage. Two representative tests are described in Table 2-1.

The system is rated to ensure that there will be sustained service to a load if an outage as long as 10 secs in duration occurs. It is therefore designed with ample margin to allow time for synchronization and reconnection to the utility once the outage is over. Long outages of up to 30 secs were used to determine the maximum time the system discharges before it shuts down.

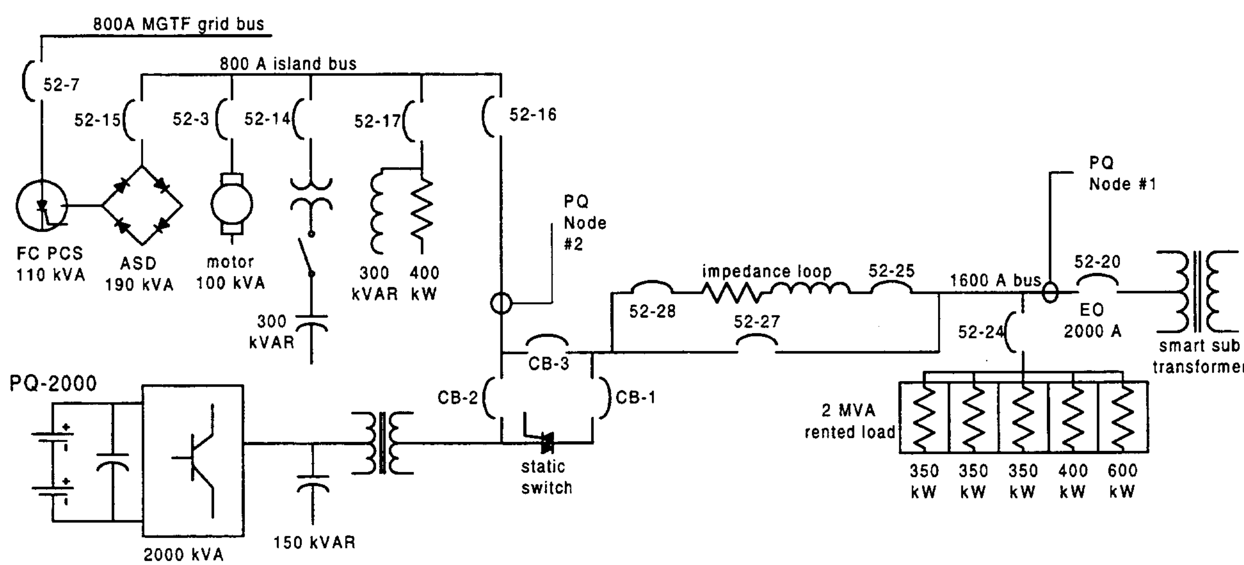

Figure 2-1. Partial-Load Test Configuration.

Table 2-1. Full-Duration Discharge; 500-kVA Resistive and Inductive Loads

Test No.	Date	3-Phase Load (kVA)	Outage Duration (sec)	Response t (ms)	Discharge Duration (sec)	Comments
1	7/22	500	30	2.5	13.4	After discharge, container and static switch shut down from loss of supply.
2	7/22	500	12.2	3	13.0	System did not synchronize in time to reconnect to grid. Failed to recharge after this test.

These discharges were typically around 13 secs as indicated. Test 2 illustrates an outage that lasts for fewer than 13 secs but that is too long for the system to adequately recognize, synchronize, and reconnect to the restored grid supply.

Loss-of-Utility Test

This test was performed to characterize the operation and speed of response of the PQ2000 to a rated 10-second loss-of-utility condition. A typical response is described in Table 2-2. In this test, 1.1 secs transpired between the time the utility was restored and the time that the system reconnected the loads to the grid.

Table 2-2. Ten-Second Outage; 500-kVA Resistive/Inductive Loads

Test No.	Date	3-Phase Load (kVA)	Outage Duration (sec)	Response t (ms)
1	7/22	500	10.2	2.8

Figures 2-2 and 2-3 show system voltage and current traces recorded using a PC-based data acquisition and graphing package during the 10-sec test. The traces shown in this plot, as well as most subsequent plots, are identified as follows:

Trace 1: Utility voltage phase A rms (Labeled 5227RMS)
Trace 2: Utility voltage phase A (Labeled 5227Vab)
Trace 3: Load voltage phase A (Labeled 5216Vab)
Trace 4: Utility current phase A (Labeled 5227Ia)
Trace 5: Load current phase A (Labeled 5216Ia)

Figure 2-2 shows the utility outage and transfer of load to the PQ2000 system. The voltage overshoot created by the PQ2000 to disconnect the utility (by commutating [turning off] the conducting static switch) is evident in the load voltage, 5216Vab. At that point, the utility current (5227Ia) drops off, and the load is maintained by the battery system.

Figure 2-3 shows the PQ2000 reconnecting the load to the utility 11 secs later. This is indicated by the return of utility-supplied current 5227Ia. The utility voltage (5227Vab) had returned a second earlier.

90% Voltage Sag

This test characterized the system response to a utility-side voltage sag to 90% of nominal voltage, thus simulating another type of disturbance that the PQ2000 was designed to mitigate. The voltage sag was artificially introduced by opening Breaker 52-27 (see Figure 2-1) so that current flowed through the reactive elements in the impedance loop.

Because of the test configuration, once the PQ2000 assumed the load, the utility load dropped to zero, and its voltage returned to normal (the current through the impedance loop dropped to zero).

Therefore, in order for this test to be carried out, the static switch reconnect settings were changed to force a minimum run time of 2 secs. Without this temporary modification to the control logic, the PQ2000 would immediately restore the "normalized" utility source, causing a rush of current through the inductors, and the subsequent voltage sag would result in another load transfer – the PQ2000 would cycle rapidly between the two sources.

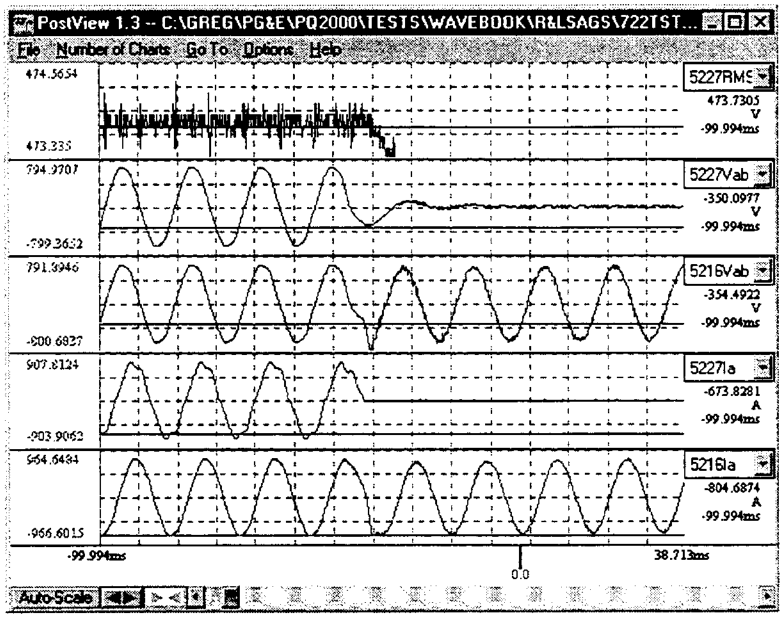

Figure 2-2. 10-sec Test: System Voltage and Current Traces at Transfer.

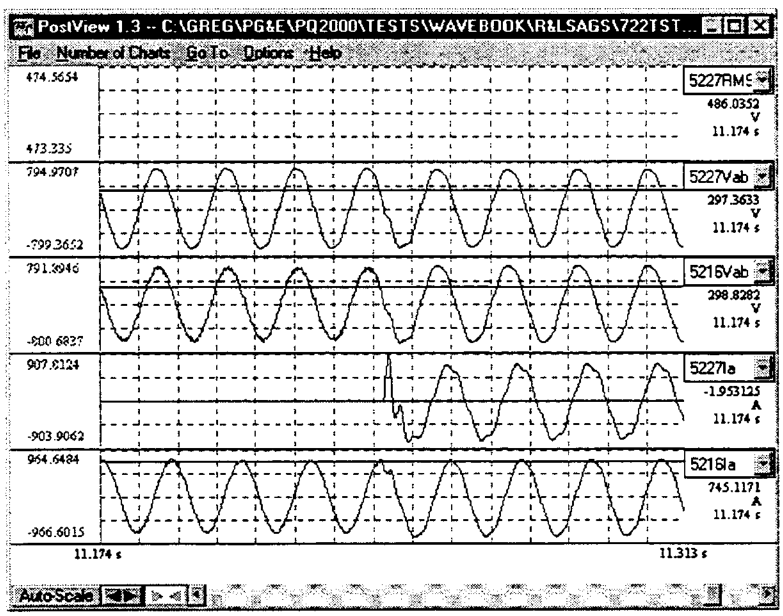

Figure 2-3. 10-sec Test: System Voltage and Current Traces During Reconnect.

One sag test (summarized in Table 2-3) was performed by slowly lowering the voltage to the trip point, so that the trip point could be accurately measured. The system tripped at just under 432 Vac, corresponding precisely with the design rating of 90% of 480 Vac. The measured load was less than 500 kVA because it was proportional to the lowered supply voltage. The discharge duration was not captured by the instrumentation for this particular test.

Figure 2-4 shows the load transfer to the PQ2000 with the phase A voltage around 432 Vac. Note that the utility voltage (5227RMS) increases immediately as the load is dropped (the voltage increase is instantaneous, but the measurement reflects the instrument's 10-cycle averaging of the RMS voltage).

Five subsequent sag tests were successfully performed by rapidly dropping the voltage to below 90%. The tests were conducted by rapidly increasing

Table 2-3. Voltage Sag Test With Nominal 500-kVA R/L Load

Test No.	Date	3-Phase Load (kVA)	Response t (ms)	Trip Voltage
1	7/22	425	2.8	~432 Vac

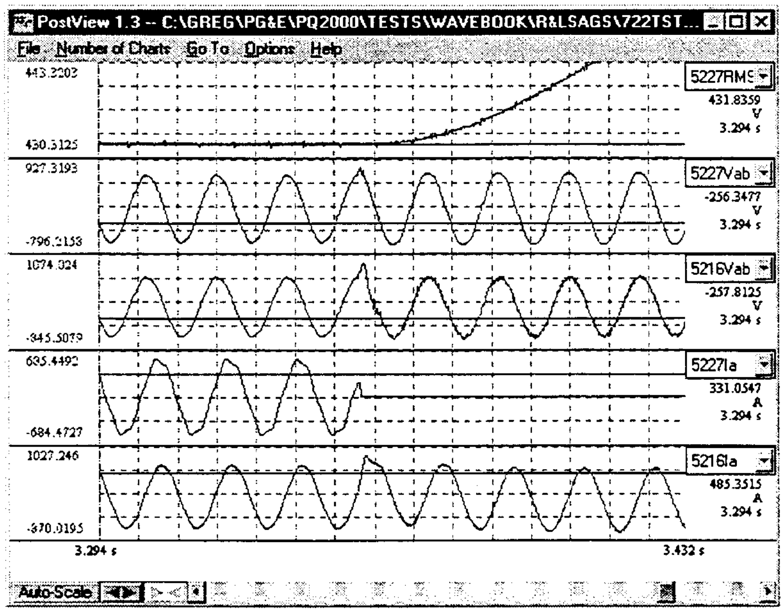

Figure 2-4. Sag Test: System Voltage and Current Traces During Transfer.

the line impedance in the impedance loop from its lowest setting (Step 1) to its maximum setting (Step 3). This effectively dropped the load voltage from a phase average of around 450 Vac to below 430 Vac. Each discharge lasted approximately two seconds.

The impedance loop setting was switched back to Step 1 during the discharge to prevent a subsequent sag from occurring when the utility was reconnected. Figure 2-5 shows the transfer from one of the fast sag tests. The sag (with averaging delay) is evident from the top trace, which is the utility phase A rms voltage. The load voltage (5216Vab) shows an almost imperceptible change as the battery system assumes the load. A slight increase in high-frequency harmonics is noticeable after the transfer.

Unbalanced Load and Sag Tests

These tests were performed on June 29, 1996, to characterize the response of the PQ2000 to an unbalanced load under a sag condition. The static switch was again set so that a two-second delay occurred between the time a normal utility voltage is detected and the system transfers load back to the utility.

The test personnel determined that the best method for creating the imbalance was to remove a phase leg from one of the impedance loop-step contactors. Two successful tests were performed in this manner, verifying the PQ2000's response to a sag in only one phase. The test was not repeated on other phases.

Operation with Partial Capacity

These tests were performed to verify the PQ2000's ability to transfer and serve partial-capacity loads with one or more modules out of service. The container was designed to handle 500 kVA of load with as few as three modules operating. The capability was verified by the following tests, all with 500-kV resistive and inductive load, on June 6, 1996.

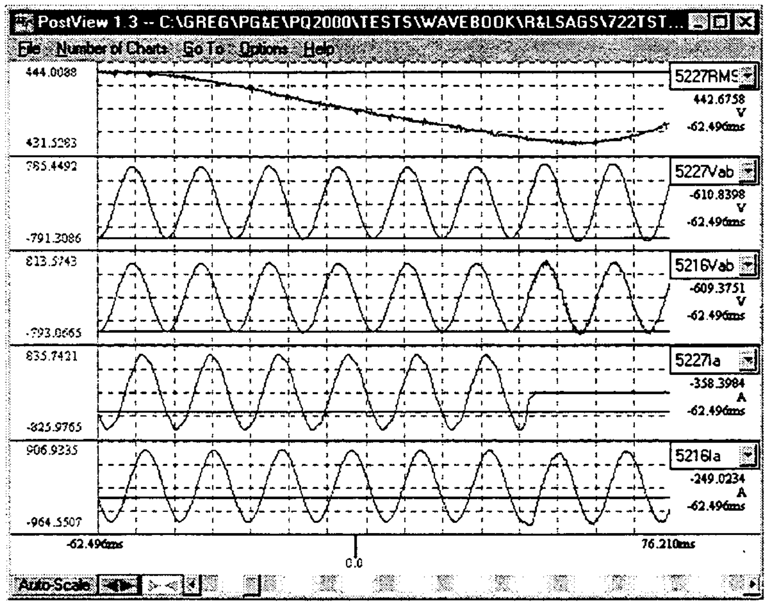

Figure 2-5. Fast Sag Test.

1. One module disabled (Module 1)
2. Three modules disabled (Modules 1, 5 and 7)
3. Five modules disabled (Modules 2, 3, 4, 6 and 8)

Repetitive Discharge Tests

A series of 43 repetitive, short-duration discharges were performed to characterize the overall reliability of the system. Each test was an outage averaging one to two seconds in duration and supporting the full 500-kVA resistive/reactive load. The tests were performed in sets of four, with a recharge period between each set. The sets were viewed as “worst case” multiple short-duration power outage scenarios.

The resistive load was dropped temporarily during transfer on at least five of the 43 tests. The bank’s over-voltage relay occasionally tripped the load as a protective measure in reaction to the PQ2000 voltage overshoot. The resistive bank also tripped once toward the end of a discharge; however, this was attributed to an over-temperature condition in the bank itself. Thus, it became evident that customers using equipment sensitive to such an overshoot should review and possibly adjust the protection settings.

The system failed to recharge following the first set of four outages. As a result, the system cut out during the fifth outage, and the load was dropped.

A "Container Over Temperature" warning was noticed on the monitoring computer at the end of the 43 repetitive tests. It was later discovered that all four container air-conditioner breakers had tripped sometime during the testing, but it is not known exactly when. The warning itself is not cause for a shutdown, which would have occurred if the temperatures had exceeded a higher set of limits. The tests therefore confirmed proper operation of the temperature warning indicator.

The system was later modified by the manufacturer to revise the charge-control software and replace the container air-conditioner circuit breakers, which corrected both of the described problems.

Figure 2-6 shows an example of a waveform from a test in which the resistive bank was shut down by its over-voltage relay. The overshoot can be seen in the negative cycle of the load voltage (Breaker 52-16). The dropped load is apparent from the decrease in load current (bottom trace) as the load stabilizes approximately five cycles after the transfer.

This plot also illustrates how the voltage harmonics increased during the unstable transition and in response to a specific load. As the waveform stabilizes five cycles after the transfer, the load current to the inductive load is very low in harmonics, but the supply voltage created by the PQ2000 through its capacitors experiences a slight resonance at the switching frequency. It exhibits a marked difference from the voltage waveform shown supplying the load in Figure 2-7.

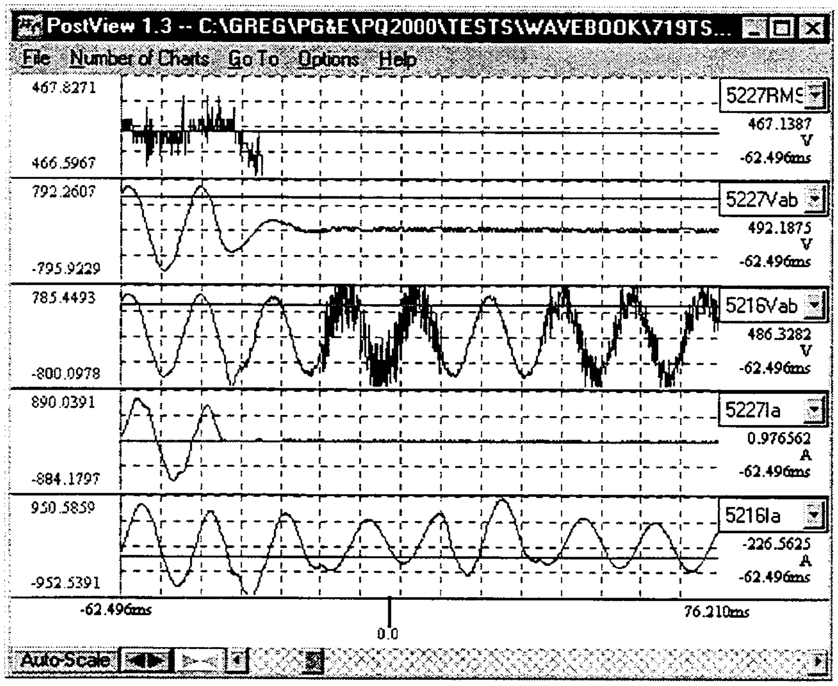

Figure 2-6. Waveform Capture of R-L Test; Resistive Load Dropped at Transfer.

Resistive and Capacitive Load

These tests used the 400-kW resistive load bank and a 12-kV, 300-kVAR capacitor bank connected via a step-up transformer from the 480-V bus. The capacitors were isolated on Breaker 52-14 to accommodate capacitor switching tests.

Capacitor Switching Test

These tests were performed to determine whether the PQ2000 is activated as a result of a voltage spike from capacitor switching. The tests were intended to simulate the field condition of utility capacitor switching on the distribution line feeding the customer.

Two types of transients were performed using the capacitor. The switch can be closed on either side of the transformer. Switching on the 480-V side creates a transient that includes the energization of the transformer, and is a more severe disturbance. The transformer is already energized when switching on the 12-kV bus; therefore, this method better replicates an actual feeder capacitor switch.

On July 23, 1996, a total of six strikes were performed from the 12-kV bus and one on the 480-Vac bus. In addition, four strikes were tested while the PQ2000 was serving the load, simulating a capacitor energizing on the load side of the PQ2000. All of these tests are summarized in Table 2-4.

The 250-kVA loads were 200-kW resistive and 150-kVAR inductive, while the 335-kVA loads were comprised of 200-kW resistive and 150-kVAR inductive. As shown in the table, all of the strikes but two were significant enough to cause the PQ2000 to discharge and assume the load—albeit for very short durations. The two strikes that did not cause a discharge were performed with light load on the 12-kV line late in the afternoon. The previous 12-kV strikes (with loading) that caused a discharge were in the morning, when the service voltage at the MGTF is typically higher.

Figure 2-7 shows the transfer that occurred in the afternoon during a 12-kV strike with no load. The current shown in 5216Ia is the capacitor coming on while the current from the utility shuts off. The strike itself can be seen in the 5227RMS trace at the top of the plot. Note that the utility voltage decreases after losing the 150-kVAR PQ2000 capacitive load.

These results confirm the benefit of off-line backup power systems with energy storage such as' the PQ2000: the system is able to provide ride-through

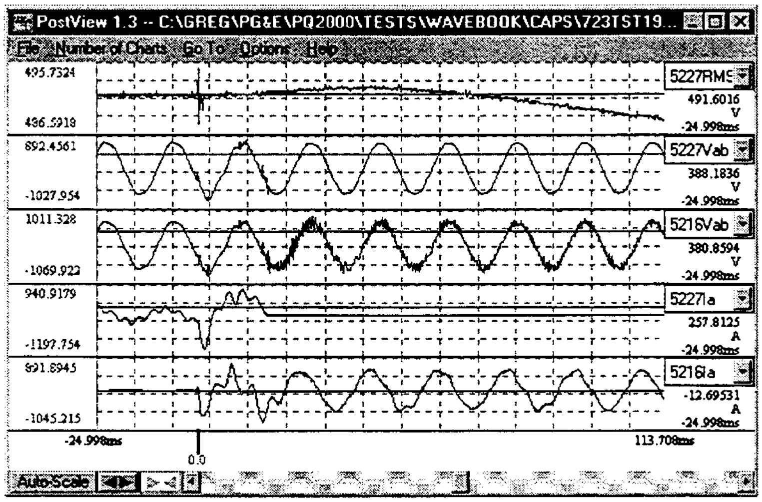

Figure 2-7. Transfer Created by 12-kV Capacitor Switching on, with No Other Loads.

Table 2-4. Capacitor Strike Tests

Test No.	Date	3 Phase Load (kVA)	Outage Duration (sec)	Strike Voltage	Comments
1	7/23	250	<1	12 kV	Discharged
2	7/23	250	<1	12 kV	Discharged
3	7/23	250	<1	12 kV	Did not discharge
4	7/23	250	<1	12 kV	Did not discharge
5	7/23	0	<1	12 kV	No load conditions; discharged
6	7/23	0	<1	12 kV	No load conditions; discharged
7	7/23	250	<1	480 V	Discharged
8	7/23	335	~5	12 kV	Strike on load during a 5-sec outage
9	7/23	335	~5	12 kV	Strike on load during a 5-sec outage
10	7/23	335	~5	12 kV	Strike on load during a 5-sec outage
11	7/23	335	~5	480 V	480-Vac strike on load during a 5-sec outage

during all types of utility disturbances, including outages, sags, and overvoltage conditions (within the storage capabilities of the system).

Figure 2-8 shows a 12-kV strike that was incurred while the PQ2000 was discharging into a 335-kVA load. This plot shows only the voltage and current to the load, traces 5216Vab and 5216Ia. A tremendous current spike is seen at the load while it is supplied by the PQ2000. Nevertheless, the system maintained the load without incident following the transient.

Loss-of-Utility Test

These tests were performed to characterize the operation and speed of response of the PQ2000 serving a resistive-capacitive load following a complete loss-of-utility condition. Two successful 10-sec carry-overs were performed and are summarized in Table 2-5. In each, the PQ2000 continued to discharge for approximately 1.1 secs after the utility voltage was restored, and then it reconnected the loads to the utility.

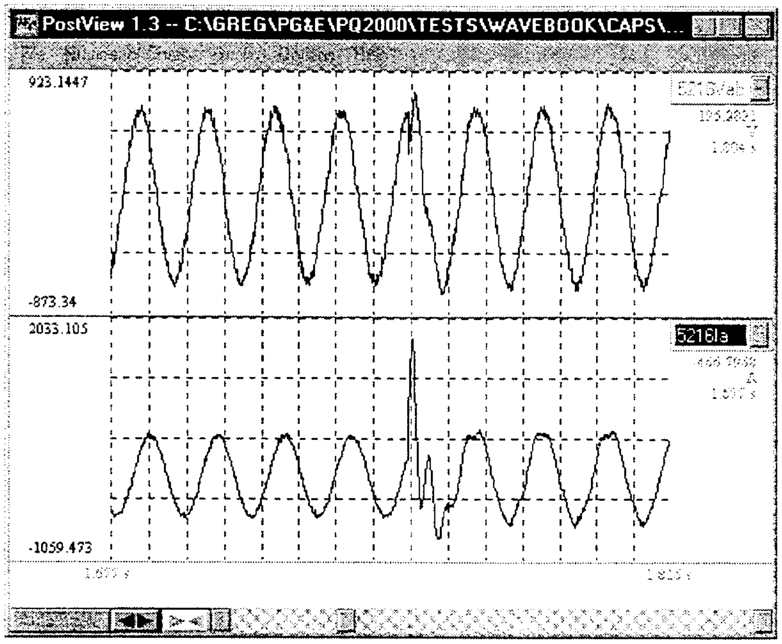

Figure 2-8. Capacitor Strike on Loads Served During PQ2000 Discharge.

Table 2-5. Loss-of-Utility Tests with Resistive/Capacitive Loads

Test No.	Date	3-Phase Load (kVA)	Outage Duration (sec)	Response t (ms)
1	7/23	500	9.82	3
2	7/23	500	9.97	3

Figure 2-9 shows the load transfer to the PQ2000 during one of the 10-sec outage tests, with a 300-kVAR capacitive load (500-kVA total load). The oscillations on the load current shown are significant, but were typical during a transfer with such high capacitive loads. The current typically stabilized after about four cycles.

Repetitive Discharge Tests

Repetitive short-duration discharges were successfully performed using the resistive-capacitive loads. As in the case with the resistive-inductive loads, the discharges were performed four at a time with interim recharges after each set of four. The discharges ranged from one to two seconds in duration.

Resistive and Rotating Machine Load

A motor-generator set was rented to facilitate rotating load testing. The motor was connected to the supply at Breaker 52-3 and was coupled to the generator via a belt drive, which, in turn, supplied an independent resistive load bank. With the generator supplying 100 kW to the load bank, the total motor load seen by the utility was approximately 160 kVA. These tests used the facility resistive and inductive load banks individually and together with the motor to provide a variety of load combinations. Tests with the motor were performed from July 24 through 29.

Loss-of-Utility Test

These tests were performed to characterize the operation and speed of response of the PQ2000 while it was serving the motor loads following a complete loss-of-utility condition. Table 2-6 summarizes six characteristic tests performed with a variety of load combinations and outage durations.

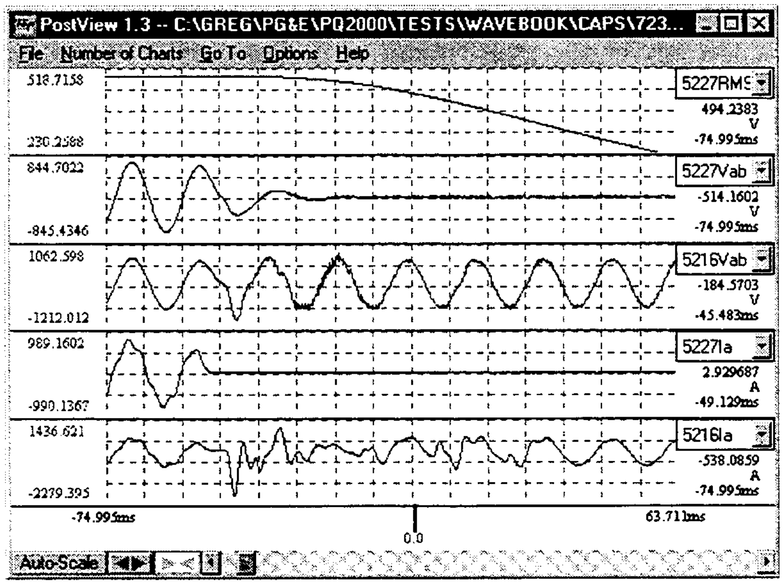

Figure 2-9. Transfer with 300-kVAR Capacitive Load.

Table 2-6. Loss-of-Utility Tests Serving Motor Loads

Test No.	Date	3-Phase Load (kVA)	Outage Duration (sec)	Comments
1	7/24	160	3	Motor only (gen loaded with 100-kW resistive load)
2	7/24	160	8.5	Motor only
3	7/29	160	9.59	Motor only
4	7/29	160	12 cycles	Motor only
5	7/29	160 kVA + 300 kW	10	Motor + 300-kW resistive **[load?]**
6	7/29	160 kVA +225 kVAR	1	Motor + 225 kVAR

Figures 2-10 and 2-11 show a successful transfer and reconnect of a motor-based load with 300 kW of additional resistive load. Several interesting aspects of powering the motor loads were revealed and are described further below.

Audible current oscillations occurred when the PQ2000 was serving the motor load. The oscillations themselves did not cause a loss of stability or load, but sometimes the current magnitude varied by 50% or more. This led to some concern over whether the oscillations would present a more serious problem at loads approaching the 2-MVA rating of the system.

The oscillations typically occurred at two times during an event. The first was when the battery first took the load from the utility. These dampened within one second. The second, and usually the more significant occurrence, was when the utility supply was first restored (not when the load is reconnected to the utility, but when the PQ2000 first detected that the supply was restored). At this point, the PQ2000 began to track the utility phasing in order to synchronize. It is this tracking that caused the oscillations.

Figure 2-12 shows the beginning of a current oscillation in the motor (bottom trace) after the utility voltage is restored (but before the load is transferred back). The plotting software was incapable of displaying a full period of oscillation on a single plot, but this period was approximately 20 cycles. The magnitude of the oscillations eventually dampened, and the utility was restored. On no occasion was there any loss of load.

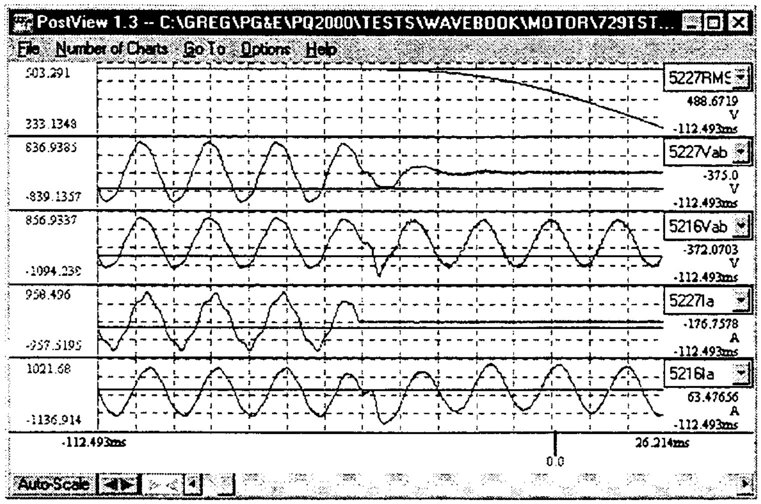

Figure 2-10. Transfer with Motor and Resistive Loads.

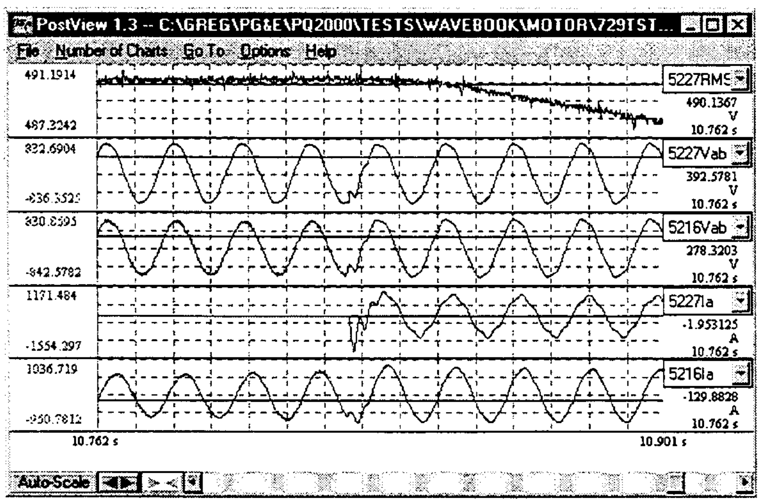

Figure 2-11. Utility Reconnection with Motor and Resistive Loads.

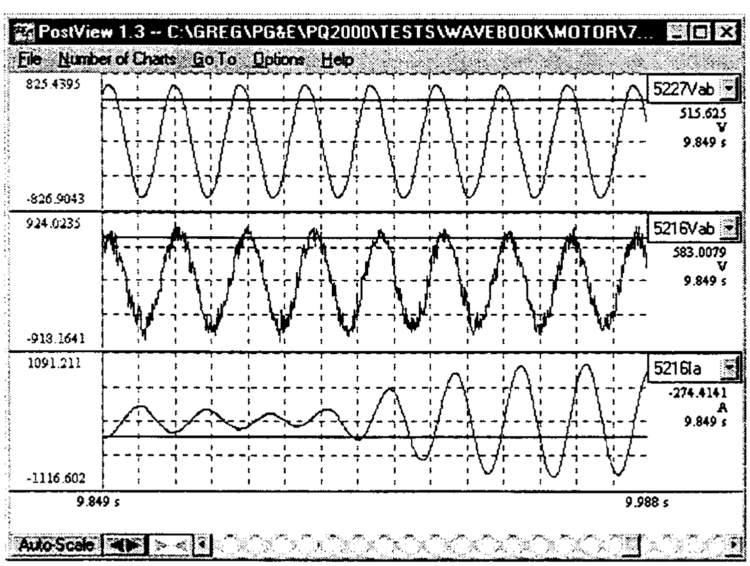

Figure 2-12. Motor Current Oscillations During Resynchronization.

In the chart, 5227Vab shows the newly returned utility source voltage. The load voltage shown in the 5216Vab is the back-electromotive force of the motor load, initially low in frequency relative to the utility. At the reclose (not shown), currents from the utility and load were at fault levels. Oscillations during resynchronization are discussed in more detail in Chapter 4, Conclusions.

Motor Starting

Two additional tests were performed to characterize the operation of the PQ2000 in response to a motor in-rush current while supplying load during an outage. The motor could not be started under load, so the first test examined the motor starting without the generator load, and the second test examined switching the running generator's load from 0 to 100 kW. The PQ2000 system handled both tests successfully.

Figure 2-13 shows the load voltage and current (5216Vab and 5216Ia) at the instant the motor was started, given 100 kW of additional resistive-base load on the circuit. As expected, the in-rush current was significant and tapered off after several cycles.

Repetitive Discharge Tests

Ten repetitive short-duration discharges, each lasting one to two seconds, were performed with the motor and 300 kW, 150 kVAR of additional load. A single test was first performed to ensure proper operation. Following that, three sets of three rapid tests were performed, allowing time for the system to recharge between each set of three. The system failed to charge after the first test (this problem was later corrected through a modification to the charge control software by the manufacturer). Each of the carry-overs was successful, and at no time were any of the loads dropped. Audible current oscillations occurred as before, primarily while the PQ2000 tracked the utility supply for synchronization.

ASD, Resistive and Single-Phase Electronic Loads

A 196-kW power supply (which was previously used by PG&E as a mock source of photovoltaic DC generation) served to emulate an electronic adjustable speed drive (ASD) load. The power supply is a 12-pulse, SCR-based AC-DC converter. The DC side of the converter was loaded using a 110-kW inverter (which had been used by PG&E in connection with a molten-carbonate fuel cell demonstration project) connected to the separate MGTF grid bus.

The ASD was connected to Breaker 52-15, and the load inverter to Breaker 52-7 as shown in Figure 2-1. In addition to the ASD, a 480/120-V transformer was used to connect various single-phase loads, primarily electronic loads such as computers and printers, etc. The purpose was to verify that sensitive electronic loads are not affected adversely by the transfer or operation of the PQ2000. The voltage sag trip-point tests were repeated because of the potential voltage sensitivity of the electronic loads.

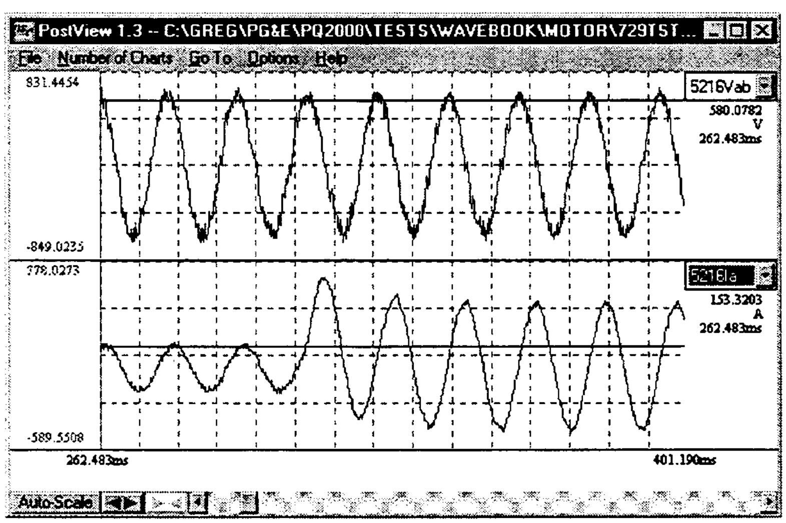

Figure 2-13. Unloaded Motor Starting During Discharge.

ASD Outage Tests

A series of ASD load combinations were configured to verify the PQ2000 response given utility outages. Table 2-7 below summarizes the 13 outage tests ultimately performed from July 24 through 25.

A recurring observation during the ASD tests was that one or both of the two power supply "legs" that formed the 12-pulse ASD rectifier would trip off during the transfer to the PQ2000. These trips were caused by the internal ASD voltage relays activating during a test, similar to those reported earlier that occurred on the resistive load banks. As indicated in the table, this happened on five of the 13 outage tests.

Figure 2-14 shows an event in which one of the two power supply legs was lost. The load current in the 5227Ia trace drops significantly as shown. In this case, the power supply trip occurred five to six cycles after the actual load transfer.

Figures 2-15 and 2-16 show a successful transfer and reconnect with just the ASD load. With a purely ASD load, 12-pulse harmonics are evident in the load current trace 5216Ia of both figures. The utility current before transfer in 5216a exhibits far more dramatic harmonic components. This is caused by the PQ2000 capacitor bank operating in parallel with the ASD. The capacitive current is not included in the load current, which is measured down line of the PQ2000. As is also evident, the voltage harmonics from the PQ2000 are more significant with a purely ASD load.

As in the case with the motor load, the ASD loads also experienced oscillations when operating in parallel with the system. The most significant oscillations took place again when the utility had been restored, and the system tracked the utility frequency before reclosing. Slight oscillations also occurred when the transfer was first made.

The oscillations are the result of the ASD trying to supply a constant current load to the inverter while being supplied by a varying frequency AC source. The variation in frequency impacts the effective DC current created by the ASD, and oscillations are created as the ASD control system tries to compensate.

A typical oscillation is illustrated in Figure 2-17. Note that the oscillation period is shorter than that of the motor load because it is caused by dueling electronic controllers rather than rotating inertia.

90% Voltage Sag Test

A test was performed to verify the system response to a 90% voltage sag while serving the ASD load. Another test investigated ramping up the ASD load from

Table 2-7. Summary of Outage Tests with ASD Loads

Test No.	Date	Outage Duration (sec)	Comments
1	7/24	3	ASD only
2	7/24	11	ASD only
3	7/24	–	ASD only
4	7/24	–	ASD only
5	7/24	3	ASD and 300 kW - Lost power supply No. 2
6	7/24	3	ASD and 300 kW - Lost both PS
7	7/24	3	ASD and 300 kW - Lost PS No. 2
8	7/24	3	ASD and 300 kW, 150 kVAR
9	7/25	3	ASD and 300 kW - Lost PS No. 2
10	7/25	3	ASD and 200 kW - Lost PS No. 2
11	7/25	3	ASD and 100 kW
12	7/25	3	ASD and 100 kW
13	7/25	3	ASD and 100 kW

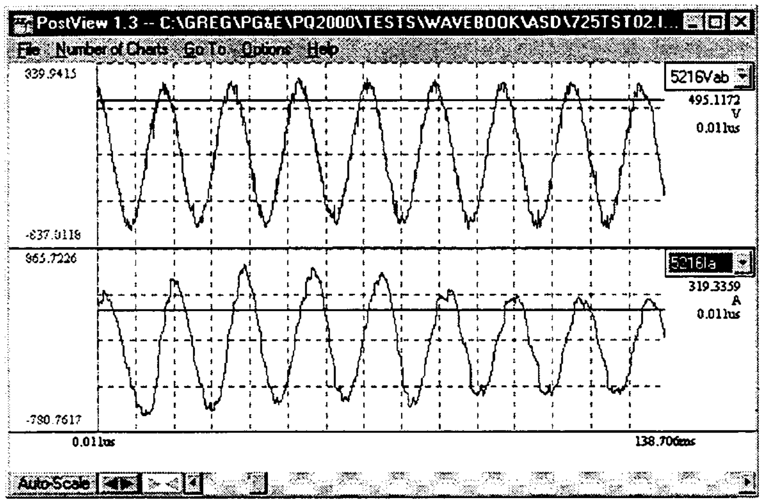

Figure 2-14. Current Drop upon Loss of One of the Two ASD Power Supplies.

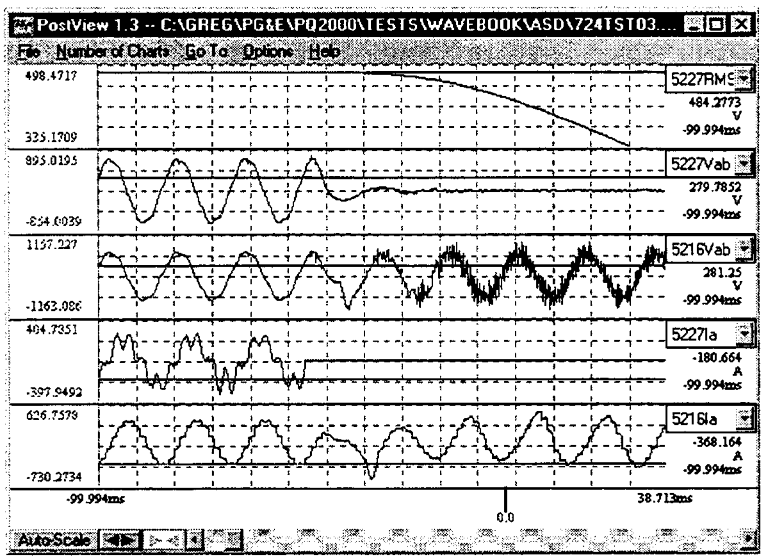

Figure 2-15. Transfer with ASD Load Only.

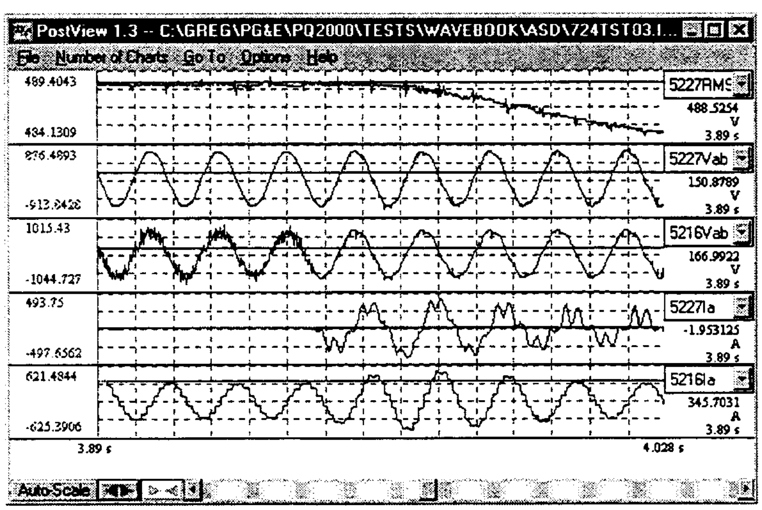

Figure 2-16. Utility Reconnect with ASD Load Only.

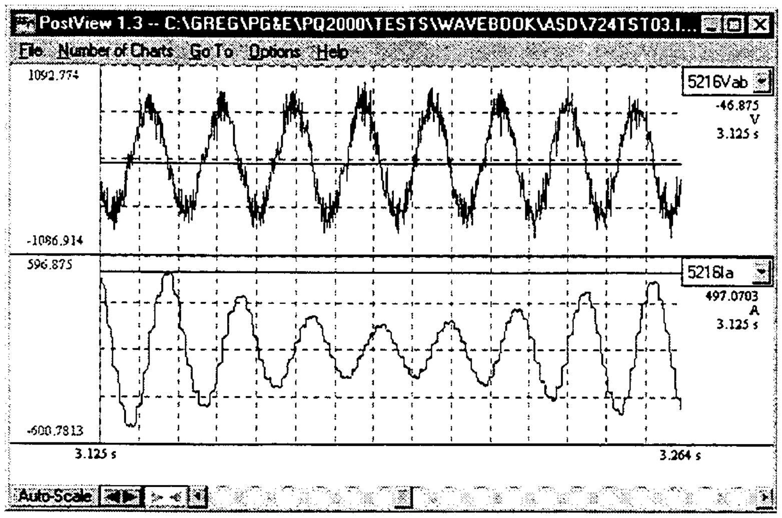

Figure 2-17. Load Current Oscillations During Utility Resynchronization Stage.

zero to full power while the PQ2000 system was discharging into a 200-kW resistive load. Both tests were successful in that no load was lost, and the PQ2000 handled the ramp-up without any problem.

Repetitive Discharge Tests

A series of repetitive short-duration discharges were also successfully performed using the ASD. Each outage was approximately one to two seconds long.

Electronic Load Outage and Sag Tests

Various tests were performed to verify the PQ2000 response to utility outages and sags while the system is serving various electronic load combinations. The 120-V load circuit consists of two PCs with monitors, a laser printer, and a TV-VCR unit.

The electronic load tests performed included:

- 120-V load circuit and 25-kW resistive load for eight seconds.
- 120-V load circuit and 400-kW resistive load for five seconds.
- 120-V load circuit, 200-kW resistive load, 225-kVAR inductive load and ASD for five seconds.
- 120-V load circuit, 200-kW resistive load and ASD for five seconds.
- Sag with 120-V load circuit, 200-kW resistive load, 225-kVAR inductive load and ASD.
- Ten repetitive outages (five with ASD base load and five with 100-kW resistive base).

Figure 2-18 shows the transfer to the PQ2000 during the light-load test, consisting of the electronic loads and 25 kW of resistive load. At the time of the transfer, one of the two computers was printing to the printers, the other was running the screen saver, and the VCR was playing. None of the electronic loads experienced any problems, and no transients were shown on the computer monitors. The plot does show, however, that the 25-kW resistive load was dropped temporarily at the point of transfer, but came back on less than half a second later.

Both of the five-second tests using the ASD resulted in the ASD's power supply No. 2 tripping off. None of the outage tests caused any problems to the 120-V circuit loads, nor were any problems to the 120-V circuit caused by short duration sags to 90%. The PQ2000 operated correctly on these sags, without impact to the loads.

Several attempts were made to create a brief sag condition that might affect the PCs if not protected by the PQ2000. However, the only condition that caused a PC reboot was when the supply voltage stayed low (below approximately 455 V) for a length of time. A short-duration drop to below 90% (432 Vac) would not cause a reboot. Therefore, a test could not be performed that would demonstrate this type of problem being solved by the PQ2000.

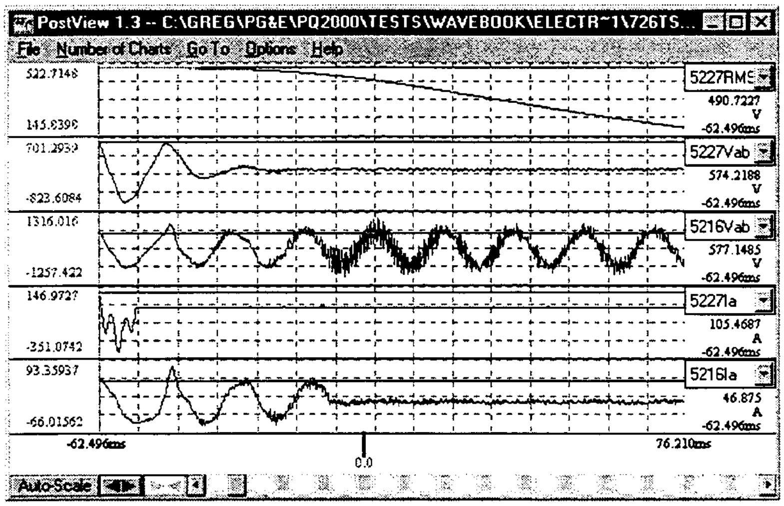

Figure 2-18. Transfer with Electronic Loads and 25-kW Resistor.

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3. Full-Load Tests

A series of tests were performed to demonstrate that the PQ2000 met its design rating of 2-MW for 10 secs. The tests included a number of initial characterization tests of various discharge lengths. Following these, a set of repetitive tests was run to assess system reliability. The PQ2000 was physically reconnected in the position shown in Figure 3-1 to accommodate the full loading.

Ten-Second Tests

These tests were designed to demonstrate the full-power and discharge duration of the PQ2000 in response to a complete loss-of-utility condition. Before these tests, various trial discharges were performed to ensure that the system had been connected in the new position properly and that it could produce the full-load current of 2400 amps (2 MVA at 480 V).

Two observations during the initial tests are worth noting. First, the system would not initially respond to full-power outages because the test loads drew currents in one or more phases that marginally exceeded the 2400-amp system rating. In such a situation, the system locked itself out of operation as a self-protective measure. To allow continued testing, the set point was raised to 2500 amps.

Second, the system initially had difficulty reconnecting to the restored utility at the conclusion of an outage. The system cycled through multiple reconnects, each separated by an internally set 12-cycle delay. Such a reconnect attempt is illustrated in the half-cycle current notch in Figure 3-2.

The behavior was attributed to voltage dips that occurred when the utility transformer first resumed support of the 2-MW load. The dips were interpreted as voltage sags or frequency excursions by the PQ2000, which responded by dropping the utility and serving the load again with the battery.

Thus, the system attempted to continue protecting the load from these sags, further confounding the testing. One explanation was that the utility transformer was not sized adequately for the testing (it was rated for 1 MVA continuous duty). The reconnection control was modified to disable the frequency detection logic during reconnect, and this facilitated the testing.

Table 3-1 summarizes the results of the ten, 10-sec tests that were performed. The phase currents for each of the tests are shown. The total apparent power from these tests ranged from 1.9 to 2.0 MVA, depending on the bus voltage. The voltage was typically low (460-470 Vac) because of the heavy loading of the utility transformer.

Figures 3-3 and 3-4 show a successful transfer and reconnect in response to a 2-MVA outage.

Short-Duration Tests

These tests were performed to characterize the reliability of the PQ2000 supplying numerous short-duration (one- to two-second) outages. The results from these tests are summarized in Table 3-2. At no time were loads lost because of a PQ2000 failure, or because of the reconnect attempts described previously. Occasionally a resistive bank tripped on overvoltage during the transfer, as indicated in the table.

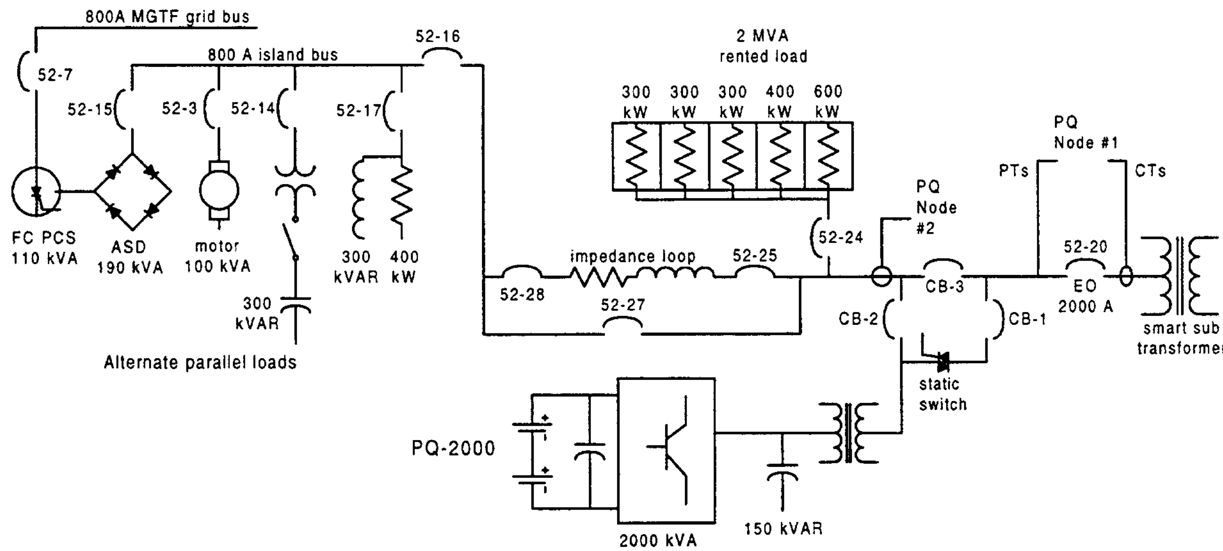

Figure 3-1. Test Configuration for 2-MVA Load Testing.

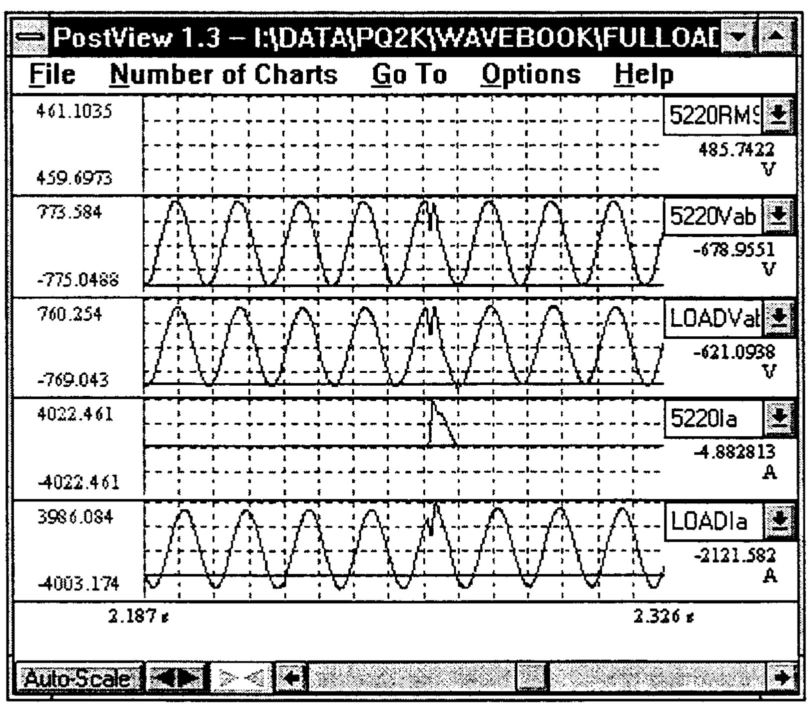

Figure 3-2. Failed Reconnect Attempt.

Table 3-1. Summary of Full-Power, 10-Sec Outage Tests

Test No.	Date	Phase A,B,C Load Current (amps)	Outage Duration (sec)	Comments
1	8/19	2406, 2346, 2408	9.89	Resistive load
2	8/19	2420, 2357, 2393	9.46	Resistive load
3	8/19	2398, 2369, 2402	9.85	Resistive load
4	8/19	2418, 2402, 2434	10.23	Resistive load
5	8/19	2414, 2391, 2424	10.5	Resistive load
6	8/20	2418, 2379, 2410	9.96	Resistive load
7	8/20	2395, 2354, 2414	10.16	Motor load included
8	8/20	2410, 2381, 2436	10.27	Motor load included
9	8/20	2406, 2367, 2430	10.07	ASD load included
10	8/20	2432, 2387, 2445	10.11	ASD load included

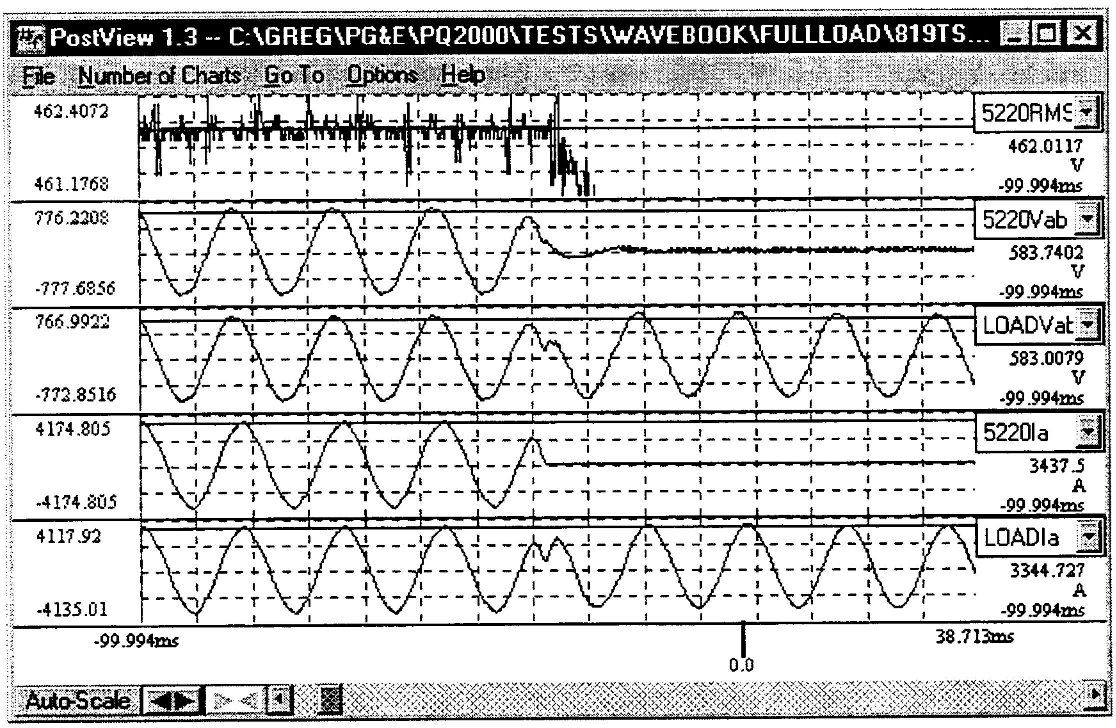

Figure 3-3. Transfer During 2-MW, 10-sec Outage Test.

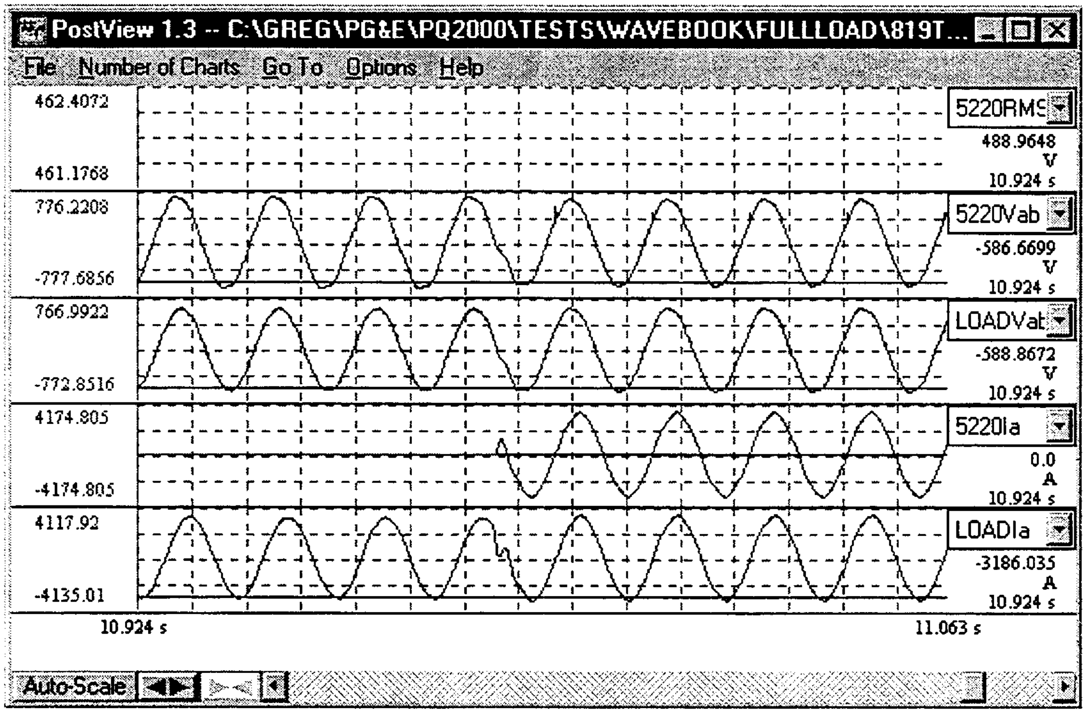

Figure 3-4. Utility Reconnect During 2-MW, 10-sec Outage Test.

Table 3-2. Summary of Results from 30 Short-Duration Discharges at Full Load

Test No.	Date	Phase A,B,C Load Current (Amps)	Outage Duration (sec)	Comments
1	8/20	2416, 2391, 2430	1.62	
2	8/20	"	1.68	
3	8/20	"	1.5	two reconnect attempts
4	8/20	2412, 2363, 2408	1.79	> three reconnect attempts
5	8/20	"	1.39	
6	8/20	"	0.68	
7	8/20	"	0.95	
8	8/20	"	0.83	
9	8/20	2424, 2377, 2414	1.39	
10	8/20	"	1.53	one reconnect attempt
11	8/20	"	1.57	
12	8/20	"	1.44	
13	8/20	2420, 2375, 2410	0.92	
14	8/20	"	0.84	400-kW load bank failed at transfer
15	8/20	"	0.96	
16	8/20	"	0.95	
17	8/20	2406, 2365, 2398	1.06	
18	8/20	"	0.82	400-kW load bank failed at transfer
19	8/20	"	1.06	one reconnect attempt
20	8/20	"	1.24	OK
21	8/20	2420, 2375, 2410	1.16	one reconnect attempt
22	8/20	"	1.51	400-kW load bank failed at transfer
23	8/20	"	1.17	OK
24	8/20	"	1.20	two reconnect attempts
25	8/21	2430, 2381, 2420	1.17	four reconnect attempts
26	8/21	"	1.28	OK
27	8/21	"	1.25	> two reconnect attempts
28	8/21	2430, 2371, 2408	1.04	OK
29	8/21	"	1.10	one reconnect attempt
30	8/21	"	1.10	OK

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4. System Design and Operation Implications from Test Results

In the course of testing, a number of lessons were learned with respect to the design and application of off-line, reserve-power systems that utilize energy storage. Some of the issues that surfaced led to on-site design modifications of the prototype itself, some led to improved designs for subsequent generations of the PQ2000, and some remain unresolved.

The items reported below have been selected based upon their applicability to the technology and application in general. Design issues considered specific to the PQ2000 are not addressed.

System Design Ratings

From the outset of the project, the 2-MW, 10-sec performance envelope was specified. The rationale for this rating was in part based on the physical design of the predecessor battery energy storage product that had been developed by the manufacturer. The 10-sec rating was selected in part on the basis of the required startup time for rapid-start diesel generators, such as those used for emergency backup in hospitals and other time-critical applications.

In meeting with several potential customers, however, the rating selections were called into question. Some customers found that the 2-MW size exceeded the combined size of their critical-load circuits, and some found that the 2-MW size was not large enough.

The manufacturer has developed design concepts for multiple product offerings partly in response to these findings, with ratings of 250 kW, 500 kW, and 1 MW (Meyer, 1998). One system, which the manufacturer fielded shortly after the prototype, was based on the same basic 2-MW design, but included only four of the eight battery modules, giving it a system rating of 1 MW. The system underutilized the container space but met the load requirements of the customer.

The 10-sec discharge capability was also called into question. Many diesel generators, particularly generators that are more than a few years old, have longer start times, typically in excess of 15 secs. Some backup power systems are not designed for rapid start at all (rapid-start systems generally circulate warm oil for immediate starting and loading). These systems would require bridging intervals of 30 to 60 secs.

The PQ2000 prototype was designed so that each component was capable of operating at full power for 100 secs (with the exception of the battery, which was designed for 50 secs). Thus, while there is an inverse relationship between discharge duration and battery cycle life, the PQ2000 rating was to some extent arbitrary. The 10-sec limit, which was "hard-coded" into the control logic as a precautionary measure, was viewed as a conservative rating appropriate for the first generation unit. Subsequent units with essentially the same hardware components were rated for 15 secs, and it is anticipated that the time ratings will be increased further as more field experience is gained.

Cost trade-off analyses should be performed by suppliers and customers alike to determine when the cost of additional storage capacity exceeds the costs associated with the purchase and use of rapid-start generators.

The physical constraints governing the time rating relate to the heat generated in the power train during discharge. While the actual heat transfer relations are affected by ambient temperature, internal air flow characteristics, and other complicating factors, a reasonable first-order approximation may be made by assuming that the overall system rating is determined by the maximum system power rating in MW and the total energy rating in MW-seconds (or "megajoules").

Thus, if the system were rated for 10 secs at 2 MW, it should also be capable of dispatching one MW for about 20 secs without exceeding the power train thermal limits. The final envelope ratings will be determined by the manufacturer.

It is worth noting (Meyer, 1998) that UPS manufacturers generally design and rate equipment with a maximum apparent power at 0.8 power factor. This practice penalizes on a dollar-per-kVA basis those systems that are designed for the same apparent power regardless of power factor (such as the PQ2000).

As such, if the PQ2000 could be redesigned with increased ratings for the power electronics to provide about 2500 kVA at 0.8 power factor (while retaining the 2000 kW rating at unity power factor), the overall improvement in dollar per kVA would far outweigh the incremental system cost on a dollar-per-kW basis.

All of the above issues—the preferred power ratings, the treatment of energy versus temporal ratings, and the assumed power factor—remain for the marketplace to resolve.

Reconnection Logic

Utilities often use breakers that automatically reclose several times after an initial trip in case the fault is transient or self-clearing in nature. If these reclosing operations (which generally are timed for a few cycles up to a few seconds) fail, the device locks in the open position for safety, requiring manual reset by utility service personnel. Most outages correspond to the duration of the reclosure settings because faults clear more often than not. Faults that do not clear on their own are more serious, requiring utility inspections, repair, and manual device resets. Such faults result in outages of hours or days.

Under the typical utility distribution scheme, therefore, backup power systems with ratings higher than the maximum reclosure settings ensure reliable power for momentary outages, but not extended outages. Customers installing such systems can maximize the effectiveness by coordinating their protection plan with the utility distribution engineering staff.

There are occasions, however, when the time required for reserve-power is comparable to the backup system time rating. In a case where the maximum reclosure setting is 2 secs, there are times when 5-sec or 10-sec protective capability in which avert a disruption to end-use loads. Voltage sags originating in the transmission system ("brown outs"), for example, can expose loads to out-of-tolerance conditions for many seconds and, depending upon the type of equipment, can cause loss of load and costly downtime.

It follows that the design of the reserve-power system should consider outages of any possible duration. The cases shown in Table 4-1 may be generalized, given that the reserve-power system has a finite energy storage capability and that a short (one to two seconds) period is required for resyncronizing with the utility.

Of these, Cases 1 and 5, momentary and long-term outages, respectively, are considered the most common. Case 1 corresponds to the condition in which the disturbance lasts only a few cycles or a few seconds. The reserve-power system is able to carry the load during the disturbance, resynchronize with the utility when it is restored, and transfer the load back to the utility. Case 5 would represent a long-term outage in which case the reserve-power system is forced to shut down, the load is lost, and the system returns to normal once the utility is restored.

During the course of testing, it became clear that the system must also be designed to handle the situations

Table 4-1. Utility Reconnection Schemes for Energy Storage Systems

	Description	Desirable System Response
Case 1 (momentary outage, most common)	Utility is restored with adequate time to resynch.	System resynchs with utility and reconnects load.
Case 2	Utility is restored without adequate time to resynch.	Either (1) connect load out of phase to preserve continuity of power to load, or (2) drop load and restart after delay.
Case 3	Utility is restored immediately after energy storage is depleted, before system shutdown is completed.	Depending upon design, may have to force lock-out to complete shut down and start-up sequences. Outage at load is extended.
Case 4	Utility is restored shortly after complete shutdown.	Voltage may be present on load side because of back-electromotive force from motors winding down. May want time delay or sensing to ensure smooth start up.
Case 5 (long-term outage)	Utility is restored long after complete shutdown.	Start-up sequence initiated when utility is within tolerance.

illustrated in Cases 2 through 4. In Case 2, the utility is restored, and the reserve-power system begins to resynchronize with the utility. Depending upon the types of loads, the phase difference at the time of restoration, and other factors, the time to resynchronize may be a fraction of a second up to several seconds. However, the energy storage is depleted (or the system is otherwise constrained) before the system can fully resynchronize.

In this situation, it is not clear whether the system should reconnect the load to the utility before shutdown. Connecting the load would ensure continuous power to the load. However, the transfer would take place out of phase, possibly causing faults or damage to equipment.

If an outage were to extend beyond the point at which the energy storage is depleted, the system shuts down and the load is lost. However, the system may require an orderly sequence of events during shutdown (and later start-up), so if the utility is restored during the shutdown sequence (represented by Case 3), it may be desirable to include a lock-out or time-delay device to ensure that the shutdown is completed before start-up begins. In effect, this provision extends the duration of the outage.

The final case (Case 4) represents the situation in which the utility is restored and the shutdown is complete. However, if unprotected motor loads are present, a back-electromotive force is generated as the motors spin down. If the utility is restored while the motors are still spinning (up to several minutes after the load is lost), it may be problematic to restore power because the load and source are out of frequency. Restoring the load may cause excessive torque on the motor shafts and/or electrical damage to the motors.

Figure 4-1 shows a motor load that reconnected about 1.5 secs after the PQ2000 stopped its discharge. The utility was restored only about ¾ sec before the reconnect as the motor was slowing down. The utility closed in while out of phase, and the resultant surge tripped the utility breaker and damaged the insulation of the motor's input cabling.

In the figure, the second trace is the newly returned utility source voltage. The load voltage shown in the third trace is the back-electromotive force of the motor load, noticeably under frequency relative to the utility. At the reclose, currents from the utility and load shown are at fault levels.

Industrial motors have protective circuitry built in, and it may be sufficient to rely on such circuitry to prevent motor reconnection in a potentially damaging situation. Alternatively, the system could include a site-specific time delay or voltage-sensing circuitry to prevent this from happening.

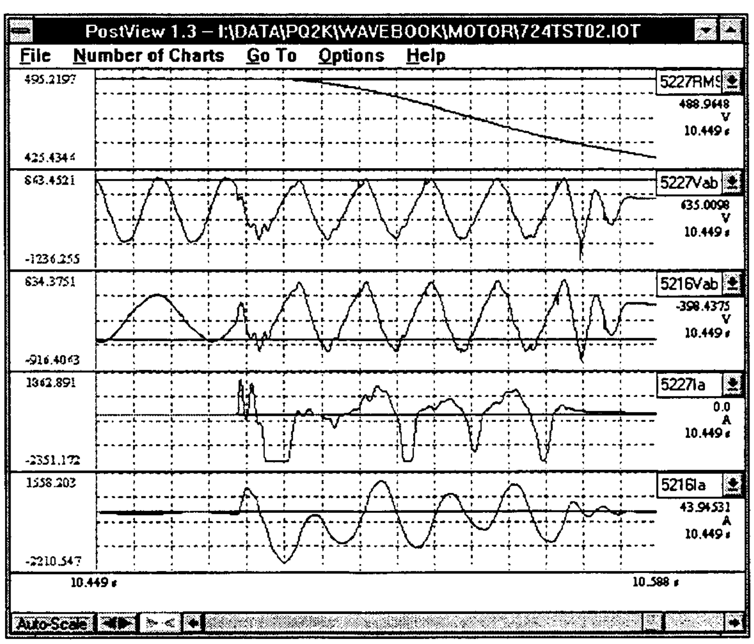

Figure 4-1. Out-of-Phase Reclose on Decaying Motor Load.

Switch Commutation Impacts

When the PQ2000 begins to transfer load from the utility to the battery, it immediately ramps up its output voltage to 110% of the pre-fault utility voltage. The overshoot is used to commutate (turn off) the SCRs that connect the load to the utility. Throughout the partial-load tests (500 kVA or less), these overshoots periodically caused certain sensitive control power circuits in the adjustable speed drive (ASD, a 12-pulse SCR rectifier) and the 400-kW resistor bank to trip off.

The manufacturer reports that the overshoot has been reduced to 5%, and this should mitigate the problem. In an actual field installation, it would be prudent to coordinate the voltage overshoot with the settings of various critical loads, thereby preventing unnecessary loss of load.

Synchronizing with Utility/ Oscillations

Audible current oscillations occurred during testing when the PQ2000 was serving either the motor or ASD load. While in no test did the oscillations cause a loss of stability or load, the current magnitude did vary significantly. The test facility constraints prevented a more thorough examination with similar loads approaching the 2-MVA rating of the device.

The oscillations typically occurred at two times during an event. The first was when the load transferred from the utility to the battery system. These were observed to dampen within one second. The second, and usually more noticeable occurrence, was when the utility supply was first restored and detected by the system. At this point, the PQ2000 would track the utility phasing to resynchronize, causing the oscillations as shown in Figure 4-2.

Such oscillations can, in general, be expected with loads that react dynamically to supply frequency variations. Rotating inertia in motors and the nonlinear control of electronics-based drives may actively oppose the frequency control and tracking inherent in off-line UPS systems. The interaction may be quickly damped, or it may set up larger oscillations.

In either case, this is a highly site-specific and load-specific phenomenon. Therefore, customers with this type of load will need to pay careful attention to their interaction with off-line reserve-power systems.

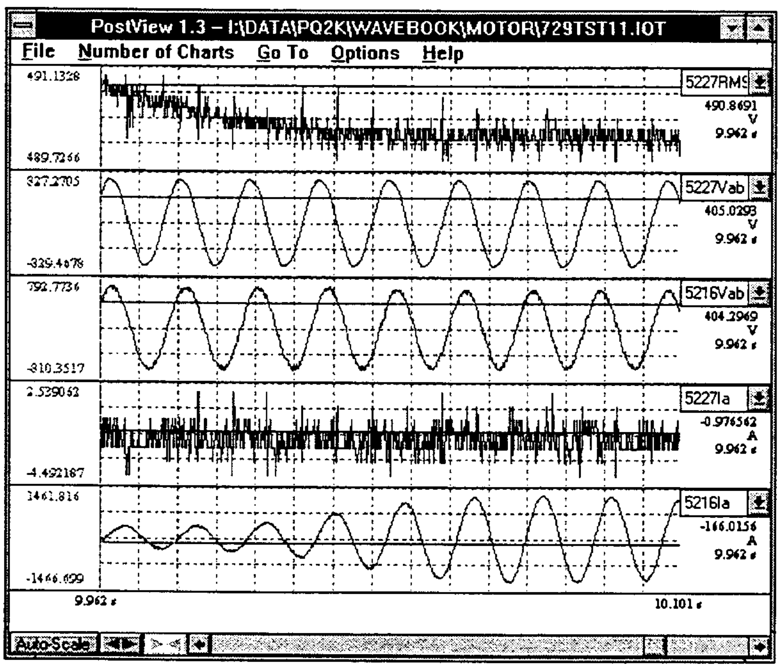

Figure 4-2. Motor Current Oscillations.

Frequency Detection

The initial control specification called for dispatch of the PQ2000 in response to utility-side sags, swells, and outages. However, early loss-of-utility tests with the motor load revealed the necessity to incorporate frequency detection in the load-transfer logic. At the point in which the utility was dropped, the PQ2000 interpreted the back-electromotive force of the motor as in-tolerance utility supply. Therefore, the system did not discharge until the motor output dropped in voltage, at which time the motor frequency was about 58 Hz. The system discharged at 60 Hz, causing abnormal stress on the motor shaft.

This observation led to the introduction of frequency detection as part of the load transfer logic (test results reported earlier were taken after this logic was in place). As detection of utility disturbances is integral to any off-line reserve-power system technology, it was concluded that frequency detection ought to be considered in all such designs.

Energy Loss Savings

An important benefit of "off-line" UPS configurations, exemplified by the PQ2000, is the cost savings associated with its reduced loss of energy. Conventional "on-line" UPSs (see Appendix A) provide continuity of power by continually rectifying the primary utility power source to a DC bus and then inverting the power to supply the load. These processes, shown in Table 4-2, can result in significant economic impact.

Table 4-2. UPS Energy Loss Processes

	On-line UPS	Off-line UPS
Rectification losses	Continuous	Only during post-dispatch charging
Battery charge/ discharge losses	Only during dispatch	Only during dispatch
Inversion losses	Continuous	Only during dispatch

The cost of these energy losses depends upon the system ratings, the customer rate schedule, the conversion efficiencies, and the frequency of utility source disturbances. However, the results of a sample calculation are provided below using the assumptions shown in Table 4-3.

The on-line UPS delivers 5,256 MWh to loads over the course of a year. To meet this load, the system incurs inversion losses of 219 MWh and rectification losses of 112 MWh. Losses associated with round-trip battery efficiency are negligible – the total annual energy delivered during outages is only 33 kWh – as are the rectification and inversion losses associated with stored energy. Therefore, the total annual energy loss is 331 MWh. Table 4-4 summarizes loss amounts.

Table 4-3. Energy Loss Assumptions

UPS Rating	1 MW - 10 secs
Efficiency – Rectification	98%
Efficiency – Inversion	96%
Cooling coefficient of performance	3.0
Average cost of power (combined demand and energy charges)	$80/MWh
Utility disturbances per year	12 (complete discharges)
Battery DC round-trip efficiency	80%
Load factor	60%
Service life	10 years
Inflation	3%
Discount rate	8%

Table 4-4. Sample Energy Loss Calculation for 1-MW UPS

Energy Delivered to Loads	5,256 MWh/yr
Losses:	
Inversion	219 MWh/yr
Rectification	112 MWh/yr
Battery	Negligible
Cooling	110 MWh/yr
Total Loss	441 MWh/yr
Total Energy Consumed by Customer	5,697 MWh/yr

The UPS also incurs an energy penalty in removing this heat from the battery room (excess temperature can result in shutdown of the UPS protection). Power for cooling is about 110 MWh, bringing the total annual energy impact from losses and heat removal to 441 MWh, valued at $35,300.

The system is assumed to have a 10-year service life, which may be longer than the battery life. For purposes of calculating energy losses, the number of battery replacements is not relevant. Taking into account inflation, the value at present of these annual losses is $288,000, or $288/kW.

Off-line systems do not incur continuous rectification and inversion losses, and the losses associated with support of dispatch events are negligible as in the on-line case. Both configurations incur parasitic losses associated with control power. Also, the off-line system is assumed to incur static switch cooling losses about equal to the fan power consumption in the UPS, both of which are therefore excluded for purposes of this analysis.

The overall energy loss penalty for an on-line system, therefore, is nearly $300/kW. While the market pricing of UPS systems varies considerably depending upon system specifications, the energy loss penalty can account for as much as one-third of the total system capital cost.

Energy Management/Power Quality Multimode Operation

With energy storage located on the customer side of the meter, it is reasonable to ask whether this energy could be used to provide additional economic benefits by reducing the monthly demand charge and the energy component of the customer's electric utility bill. Providing both "peak shaving" and reserve-power capabilities is referred to as "multimode" operation.

The question of designing a cost-effective multimode energy system revolves around the following issues:

- *Reserve Capacity.* It is anticipated that the power management feature will provide economic benefits that are secondary in magnitude to reserve-power. By reducing the energy storage capacity through the dispatch of on-peak power, the ability of the system to provide reserve-power is reduced (both the energy stored and the thermal capacity are impacted). A multimode system will therefore have to be designed with an additional margin to handle both dispatch types, and the cost of this margin reduces the overall economic justification for multimode capability.

- *Voltage/Current Sourcing.* Most peak-shaving systems operate by sourcing current to the system, which is supported by the utility. Reserve-power is supplied when the system is disconnected from the utility and operating as a voltage source. Therefore, these multimode systems will have to be designed with both voltage and current source modes of operation, and control logic and circuitry to switch between them. For on-line systems, this is not an issue because the loads are always supplied in voltage-source mode, and peak shaving can be accomplished through reducing the load as seen by the utility.

- *System Ratings.* As peak shaving is supplied over many minutes or hours, the thermal design of the power train is handled as a steady-state system. Thus, the cost advantage gained by designing the PQ2000 in accordance with transient thermal ratings is lost, and the overall system ratings decline significantly. In the case of the PQ2000, for example, the container rating of 2 MW (short term) would be reduced to 200 – 250 kW (steady-state).

Reduced steady-state system ratings impact the overall economic justification by reducing the amount of captured demand reduction and peak energy savings. Using the PQ2000 prototype as an example, the customer would size the reserve-power system according to the total peak-power consumption (2 MW), but would only capture demand-reduction savings according to the steady-state rating (250 kW), only one-eighth the total load.

Rating incompatibility is not an issue for in-line reserve-power systems because they are already rated for continuous power draw. However, these systems do not take advantage of the transient ratings afforded by off-line systems.

Ultimately, the market will determine whether multi-mode systems can be produced at a cost that justifies the dual reserve-power and energy management benefits.

Energy Storage Technology

It is important to note that the primary challenge facing the UPS industry today—the reliability of lead-acid batteries—was never an issue during the course of testing the prototype PQ2000. The batteries performed flawlessly throughout the testing period. This is largely believed to be because of the high state-of-charge (SOC) maintained on the batteries, a direct result of the overall design approach.

The PQ2000 is designed to handle only momentary outages, typically a few seconds. Even the longest discharge (10 secs) results in a reduction in the SOC by only a few percent. This contrasts dramatically with the market application of conventional UPSs, which handle outages spanning many minutes, reducing SOC by as much as 80 percent, and introducing multiple battery failure modes.

The battery selected for the prototype PQ2000 appears to meet all of the application requirements for the short-term discharges of its intended market, and it is expected that the failure mode of this battery will be corrosion of the internal plate grids. This failure mode is related to calendar life (approximately five years) rather than discharge history.

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5. Conclusions and Further Research

Diesel Integration

A key potential attribute of the PQ2000 design concept is the ability to provide "bridging" support between the onset of the utility disturbance and the start-up and load transfer to a diesel generator set. By integrating the PQ2000 with a diesel generator, the technology could provide protection against disturbances and outages of any duration, and the transfer of supply from the utility to the reserve system would be seamless.

Combining the PQ2000 with a diesel generator, however, requires additional development work on controls. The current controls have been demonstrated to detect the utility disturbance, transfer load to the system, disconnect the utility, provide voltage source to the load, resynchronize with the restored utility, and transfer back to the utility.

Coordinating the PQ2000 operation with a diesel would require the additional control capability of commanding the diesel to start, bringing the diesel to speed, transferring load to the diesel, and disconnecting the PQ2000. Because both the PQ2000 and the diesel are voltage sources, the transfer to the diesel would entail either (1) synchronizing the two sources prior to closure, or (2) transitioning the PQ2000 to a current source after connecting the diesel.

A logical follow-on activity would involve a design phase and a demonstration phase. Because the market would demand compatibility with a number of diesel engine makes, the demonstration might involve operating the system with several different engine generators, obtained through rental sources.

Medium-Voltage Interconnection

Another potentially important area of further development concerns the interconnection voltage of the off-line reserve-power system. The PQ2000 prototype had an interconnection of 480 V (3-phase), which is a common standard for utility service entrances of commercial electric customers.

However, the PQ2000, with a rating of 2 MW, would find application at larger customers (typically classified as "industrial") with higher service voltage ratings, such as 4 kV or 12 kV. These "medium-voltage" customers benefit with lower utility tariffs and more practical cable sizing at the service entrance.

It is therefore important to extend off-line reserve-power technology to accommodate these classes by providing a medium-voltage interconnection. Because the power transistors that are used are not rated for voltages of this magnitude, it is necessary to combine multiple, coordinated transistors in a series connection. A "stack" of switching elements could together meet the medium voltage; each element by itself would only carry a portion of the total voltage.

A worthwhile follow-on activity would be to develop and demonstrate a medium-voltage off-line system using current PQ2000 technology and static switch technology.

Alternative Storage Technologies

The batteries used in the PQ2000 prototype proved to be fully capable of meeting the various tests described in this report. Because the system and application do not result in the SOC dropping more than a few percentage points, the batteries are expected to provide service in the field through the end of their calendar design life.

Conventional UPSs, which provide extended outage protection on the order of many minutes, however, require batteries that are tolerant of the abuse resulting from multiple deep discharges. The single-most important technical challenge for the UPS industry is to find a battery that is capable of meeting high standards for reliability, consistency, and energy storage capacity.

A number of advanced energy storage technologies, which promise to meet these performance standards and find their place in the market, have been advanced in recent years (see Appendix A). These include the zinc/bromine battery, composite flywheels, superconducting magnetic energy storage (SMES), and ultracapacitors.

These technologies have largely been developed independently in response to a wide variety of application requirements. While each holds promise in reliability, cost, or energy density, no comprehensive comparisons of them exist on a system-level basis.

A technical assessment would encompass a complete technology assessment given current and potential technology. It would address life-cycle costs, energy densities, thermal management requirements, control issues, safety issues, manufacturability, and scalability.

Parallel Generation

Large industrial customers have critical loads exceeding the 2-MW rating of the PQ2000. In some cases, it may be possible to isolate separate circuits and protect each with a separate container. In other cases, this may not be feasible, given the load sizes and facility layout.

Under these conditions, it will be necessary to use multiple containers to serve a common load (parallel generation). However, the current state of off-line controls technology is not capable of sharing loads, and additional controls development would be required.

The development could largely be done through bench testing on a module level (each module would act as a separate generating unit). A full-scale (multiple container) demonstration could be conducted at the conclusion of the development.

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A

Outage Mitigation Alternatives

Appendix A
Outage Mitigation Alternatives

Introduction

This appendix discusses alternative technologies for outage mitigation applications. Power quality encompasses a very large range of phenomena and, therefore, a wide array of mitigation technologies. These technologies extend from reducing customer harmonics with a simple passive filter to eliminating service interruptions with a redundant utility feeder and high-power static switch (Swaminathan, 1988).

Distribution planners define an outage as the loss or operative failure of a critical component in the power system. An outage may or may not cause an actual interruption of service to a customer, depending on the redundancy of the supply and the nature of the outage. When an interruption does occur, it is defined as momentary (less than one minute) or sustained (one minute or more).

The prototype PQ2000 is an outage mitigation technology that provides backup service for voltage disturbances and momentary interruptions of up to ten seconds. If combined with a backup generator, the PQ2000 system could prevent both momentary and sustained interruptions. For purposes of this report, the mitigation technologies described here are those with applications comparable to those of the PQ2000 system; they therefore utilize energy storage of some type or another. In these applications, energy storage is required to meet the combined objectives of:

- Providing an alternate, nonutility power supply for several seconds or more, and
- Effectively providing instantaneous transfer from the primary source to the back up source.

Conventional UPS Technologies

On-Line UPS

The on-line UPS is the most common and commercially successful type available. It is the standard configuration for the dominant computer applications market and is also the most widely used in commercial and industrial load applications.

Figure A-1 illustrates the typical configuration for the on-line UPS. AC power from the utility is rectified to DC, and inverted back again to AC, in a series flow of power to the load. The battery storage is connected to the intermediate DC bus, and its charge is maintained by the rectified utility power. When the utility power fails, the DC-AC inverter serving the load draws energy from the battery. The transfer presents no transient disturbance to the load. Because the load is always fed through the two converters, the on-line UPS imposes a continuous efficiency penalty in the form of converter losses. A bypass switch is provided in case of a failure of the UPS system. The on-line UPSs are generally designed to provide between 5 and 15 minutes of full-rated backup power. Below is a summary of the on-line system's advantages and disadvantages.

Advantages

- Most reliable in preventing an interruption: AC power to the load served by same DC bus regardless of source;
- Provides consistent isolation of load from utility, and potentially superior voltage quality; and
- Large existing market, widely established technology.

Disadvantages

- Continuous energy efficiency penalty;
- More components relied upon during normal operation; and
- Most expensive design.

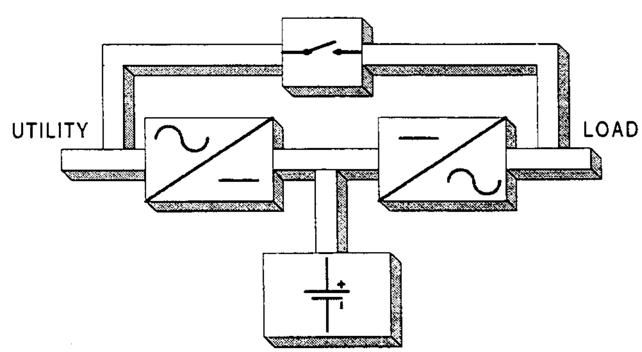

Figure A-1. On-line UPS configuration.

In comparison to the PQ2000, the typical on-line UPS is designed for longer back-up supply, and its power train components must be sized to serve continuous rated power. The UPS inverter faces the same design considerations as the PQ2000 inverter in terms of reliably, serving a variety of reactive, rotating, and nonlinear loads. However, the on-line UPS inverter has fewer design issues regarding the instantaneous pick-up of various load types from the standby mode of operation.

Off-Line UPS

The off-line UPS topology is similar to that of the PQ2000. In normal operation, utility power serves the load directly through a static switch. As shown in Figure A-2, the battery and inverter are connected in parallel to the utility and to the other pole of the static switch. When a utility disturbance is detected, the switch transfers the load to the battery-backed inverter. The off-line UPS does not have the commercial history its on-line counterpart has, mostly because of its reliance on a fast (static) transfer switch and more complex detection and transfer requirements. However, it is gaining popularity because of its inherently high operating efficiency.

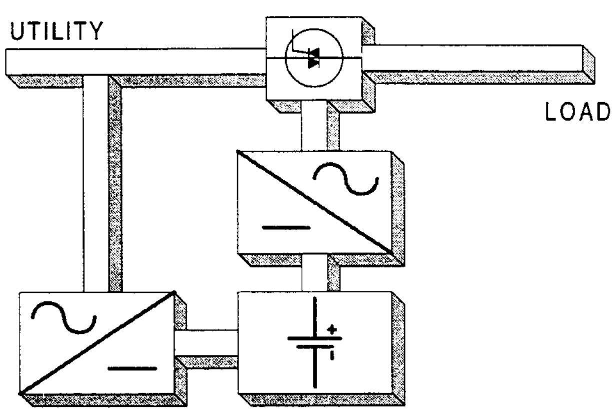

Figure A-2. Off-line UPS Configuration.

Advantages

- High efficiency;
- Power conditioning system (PCS) and battery power train components sized for shorter duration use; and
- Least expensive design.

Disadvantages

- Finite but extremely brief discontinuity in supply caused by static switch transfer;
- No inherent utility isolation; and
- Less commercial availability.

The PQ2000 differs from the typical off-line UPS by providing transient protection against voltage sags and swells, and additional filtering of the utility waveform during normal operation. The standard industry off-line UPS is also designed for longer discharges than the PQ2000—up to 15 minutes. Therefore, both the power-train components and the storage capacity of the PQ2000 are sized smaller based on short-duration ratings.

Line-Interactive UPS

A third conventional UPS technology is the line-interactive system shown in Figure A-3. It is essentially an off-line system with an additional automatic voltage regulator connected in series to provide the isolation lacking in the off-line system. As a result, it provides protection against voltage sags, surges, and transients that most off-line systems are unable to provide.

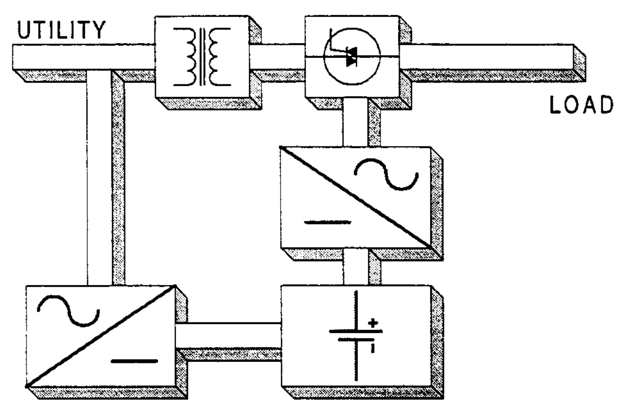

Figure A-3. Line-interactive UPS Configuration.

Rotating UPS

Standard Rotary UPS

The rotary UPS is similar to a conventional on-line UPS except that the power rectifier and inverter are rotating machines rather than electronic converters. Figure A-4 shows the configuration for the typical rotary UPS. The utility AC supply feeds an AC motor, which in turn drives an AC generator to provide the supply voltage for the load.

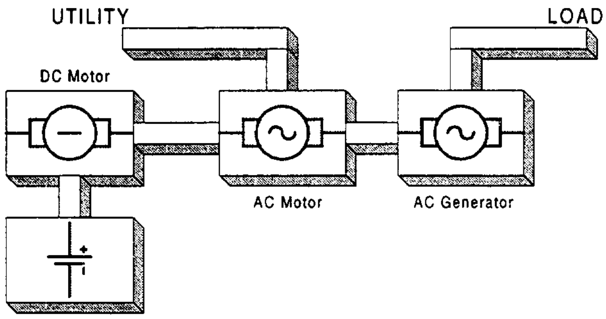

Figure A-4. Standard Rotary UPS Configuration.

Also attached to the AC motor shaft is a DC motor, which is connected to a battery bank. In the event of a utility interruption, the rotating DC motor becomes a generator fed by energy from the battery, and drives the AC motor and generator pair. No contactors or switches are required to transfer the load to and from battery, so power to the load is clean and uninterrupted.

Rotary UPSs have a sustained market serving large critical loads and are widely perceived to have superior reliability to their electronic counterparts. This type of design completely eliminates the rectifier/charger, inverter, and static bypass switch of conventional UPSs.

Advantages

- Good isolation of utility and load; clean, low impedance voltage source for load;
- Potentially superior interruption reliability over electronic switches and relays; and
- Well-established technologies.

Disadvantages

- Three rotating machines required, each rated for full load;
- Efficiency penalty in normal operation from in-line AC motor and generator; and
- Expensive.

Battery-Free Rotating UPS

A number of rotary UPS technologies utilize battery-free designs, in which energy is stored using a flywheel or other mechanical element. The most popular is commonly known as a diesel UPS, which consists of a synchronous machine, diesel generator, a free-wheel clutch, and an induction coupling with the utility.

In the event of a utility disturbance, kinetic energy stored in the inductively coupled rotors converts the synchronous motor to a generator and starts a diesel generator via the freewheel clutch. The synchronous and diesel generators provide backup for both momentary and sustained outages.

Another product uses a hydraulic flywheel with a synchronous generator, the stator of which is connected in parallel with the protected load. During a utility interruption, the flywheel causes the synchronous motor to generate to the load, providing ride-through capability and, optionally, starting torque for a backup gas or diesel generator.

The simplest battery-free design is that of the motor-generator set with a conventional flywheel shown in Figure A-5. In this system, power flows from the utility through the AC motor and generator to the load, as in the case of the rotary UPS. Brief ride-through capability is provided by a spinning flywheel connected on the shaft linking the motor and generator.

Of the three, the motor-generator system with the flywheel provides the most isolation between the load and the utility. However, both parallel-operated systems make use of the machine coupling to stabilize voltage and absorb load harmonics.

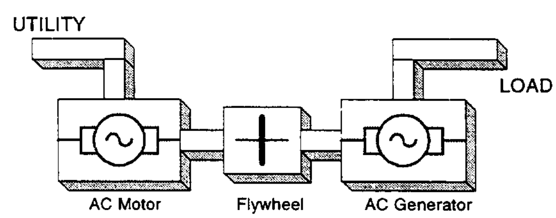

Figure A-5. Motor-generator Ride-through Configuration.

Utility-Side Solution: Dual Feed with Static Switch

Large industrial or commercial customers with high sensitivity to outages and disturbances may arrange with the utility to have the redundant supply feeder installed. The basic concept of the dual-feed approach is illustrated in Figure A-6. The second feeder originates from a substation or substation bus that is separate from the original primary feed.

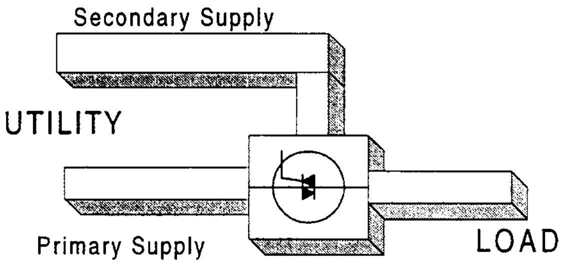

Figure A-6. Dual Utility Feed Configuration with Static Switch.

A static switch is used to transfer the customer to the secondary supply feed in the event of a disturbance on the primary feed. For disturbances that originate on the primary distribution supply, this is a highly effective and reliable solution, providing relief from sags, momentary interruptions and indefinite sustained interruptions without energy storage or fuel considerations.

However, utilities in the U.S. report that between 10% and 33% of interruptions originate on the transmission system, which supplies both the primary and secondary feed. In such instances, the dual-feed system offers no additional protection to the customer. With no customer-side equipment, this solution also does not provide the electrical isolation that is characteristic of some of the UPS systems described above.

The dual-feed solution is also limited by its expense. Typically only very large customers, or groups of customers such as in an industrial park, can justify the expense (regardless of the financing arrangement between utility and customer) of adding a new feeder. Areas where the load density is relatively high are an exception to this generalization, however, as distances between substations and load are less, and portions of the distribution system may already be networked.

Detailed List of PQ2000 Prototype Tests

B

Appendix B
Detailed List of PQ2000 Prototype Tests

Table B-1. Partial-Load Tests

No.	Category	Date 1996	Load (kVA)	Duration (sec)	Comments
1	Three outages with R/L load	7/22	500	2	Three times — one event recorded.
2	R/L outage	7/22	500	10	
3	R/L outage	7/22	500	12	
4	R/L outage	7/22	500	12	15-second outage
5	R/L outage	7/22	500	12	30-second outage
6	R/L slow sag	7/22	425	n/a	Voltage-response test. Tripped correctly between 430 and 435 Vac.
7	Five R/L fast sags	7/22	425	2	
8	Forty-three repetitive R/L	7/19	500	2-3	Lost resistive load during transfer on at least 5 tests. Lost resistive load once toward end of a discharge. Insufficient charge on first set of four. Forty-one tests were recorded.
9	Two imbalance R/L sags	7/29	500	2	Voltage trip point between 430 and 435. One test recorded.
10	Four 12-kV cap strike with R/L	7/23	250	< 1	Discharged
11	Two 12-kV cap strike w/o load	7/23	0	< 1	Discharged
12	Three 12-kV cap strike during R/L discharge	7/23	335	5	Resistive/Inductive load. One test recorded.
13	480-V cap strike during R/L discharge	7/23	335	5	
14	Cap strike (480)	7/23	n/a	< 1	
15	Two outages; cap w/400 kW	7/23	500	10	
16	10 outages; cap w/400 kW	7/23	500	2	
17	Outage; motor @ 100 kW	7/24	100	3	Oscillations
18	Outage; motor @ 100 kW	7/24	100	8.5	
19	Ten outages; motor with R/L	7/29	335 + motor	2-3	Oscillations
20	Outage motor + 300 kW	7/29	300 + motor	10	Oscillations
21	Outage motor only	7/29	motor	10	Oscillations
22	Motor start during discharge	7/29	100	10	Motor not loaded

Table B-1. Partial Load Tests (Continued)

No.	Category	Date 1996	Load (kVA)	Duration (sec)	Comments
23	Motor no-load to 100 kW during discharge	7/29	100	10	Oscillations: lost R-bank for 15 cycles at transfer
24	Outage motor load only	7/29	motor	< 1	Immediate open/close test
25	Outage motor + reactor	7/29	motor 225	1	225 kVAR
26	Outage ASD only	7/24		3	Oscillations
27	Outage ASD only	7/24		8.5	11-second test
28	Outage ASD only	7/24		10	
29	Outage ASD only	7/24		12.5	
30	Outage ASD & 300 kW	7/24		5	Lost supply No. 2.
31	Outage ASD & 300 kW	7/24		5	Lost supplies No. 1 and No. 2.
32	Outage ASD & 300 kW	7/24		5	Lost supply No. 2.
33	Outage ASD, 300 kW, 150 kVAR	7/24		5	Oscillations
34	Outage ASD & 300 kW	7/25		5	Lost supply No. 2.
35	Outage ASD & 200 kW	7/25		5	Lost supply No. 2.
36	2 outages ASD & 100 kW	7/25		5	
37	Outage ASD & 100 kW	7/25		n/a	
38	Sag ASD, 250 kW, 225 kVAR	7/25		2	
39	Ramp ASD during discharge w/200 kW	7/25		10	
40	Repetitive ASD, 200 kW, 150 kVAR	7/25		1	First test tripped supply No. 1.
41	Electronic loads	7/26		8	Two computers, printer and TV-VCR
42	Elec + 400 kW	7/26		3	5-second test
43	Elec + 400 kW	7/26		5	Fine
44	2 Elec, ASD, 200 kW	7/26		5	Lost ASD supply No. 2 both tests.
45	7 sags w/Elec R/L/ASD	7/26		2	
46	Elec, 400 kW, 225 kVAR	7/26		5	Lost ASD supplies No. 1 and No. 2.

Table B-2. Full-Load Tests

No.	Category	Date 1996	Load (MVA)	Duration (sec)	Comments
1	Initial tests	8/6	1.9	n/a	
2	Initial tests	8/6	1.5	n/a	Voltage notches
3	Initial tests	8/6	1.8	4	1 second outage — Voltage notches
4	Initial tests	8/6	1.9	> 5	1 second outage — Voltage notches
5	Initial tests	8/6	1.9	n/a	
6	Initial tests	8/6	1.85	2	
7	14 multiple diagnostic	8/7-13	1.9	n/a	
8	Initial test	8/19	1.9	1	
9	Initial test	8/19	1.9	1	
10	First 10 seconds	8/19	1.9	10	Lost a resistive bank at transfer.
11	12.5-second outage	8/19	1.9	12.5	Lost a resistive bank at transfer.
12	14-second outage	8/19	1.9	12.5	
13	30-second outage	8/19	1.9	12.5	
14	6 repetitive 10-second tests	8/19-20	1.9	10	
15	2 10-second R w/motor	8/20	1.9	10	
16	2 10-second R w/ASD	8/20	1.9	10	Lost supplies No. 1 and No. 2 on one test.
17	30 1-second resistive	8/20-21	1.9	1	Occasional voltage notches and lost resistive banks.

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List of Tests

Appendix C
List of Tests

The table below shows an overview of the PM250 testing, beginning with the delivery of the system to San Ramon, California, and ending with the final short-term characterization tests. Longevity testing is not shown, but was conducted through April 1994 by subjecting the system to a series of three-hour mock load-following cycles and periodic standard baseline tests.

Date	Test Title	Comments
10/19/93	System arrives	
10/23/93	Pre-parallel connection	
10/26/93	Pre-parallel connection 2	
10/26/93	Start-up and internal protection	
11/4/93	Baseline Test No. 2	The first baseline test performed at the Modular Generation Test Facility
11/5/93	Power quality No. 1 and PF control	BMI measurements; unable to accept signals 100-kHz spectrum analyzer single-phase plots Nicolet storage RFI measurements Audio measurements
11/16/93	Battery replacements	Not a test. Batteries 15 and 16 in Module 1 and Battery 6 in Module 3 replaced.
11/17/93	40-minute Block No. 1	190 kW Mod 2 imbalance SOC 32.9%
11/17/93	Harmonics tests	BMI snapshots taken during 40-minute block discharge, 250-kW charge, and autocharge.
11/18/93	1-hour Block No. 1	167 kW Mod 6 imbalance SOC offset
11/19/93	2-hour Block No. 1	92 kW Underproducing modules Communications problems Mods 6 and 2 imbalance 30.4% SOC
11/22/93	Module 4 responses	Few-second delay of Module 4 during command change from standby to discharge. Confirmed via independent AC current clamp (and audible).
11/24/93	Auxiliary power measurements	BMI snapshots taken on the input to aux transformer (CB9); heater, different modes BMI on Module 8, to measure blower on/off, etc. DAS measurements bogus
11/24/93	3-hour Block No. 1	66 kW Utility power blip, subsequent SCADA PC failure Module 6 imbalance

Date	Test Title	Comments
11/29/93	5-hour Block No. 1	44 kW Incomplete Communication failures Smart-sub protection
1/28/94	Qualification Test No. 1	
2/3/94	Qualification Test No. 2	
2/3/94	Qualification Test No. 3	Changed imbalance limits to +2 and –4 Vdc; Min string, Vdc from 510 to 520 Vdc
2/14/94	1-hour Block No. 2	155 kW Modules out on low voltage 520 Vdc 25% SOC
2/15/94	2-hour Block No. 2	89 kW Vdc limit returned to 510 Vdc
2/16/94	3-hour Block No. 2	65 kW
2/17/94	5-hour Block No. 2	38 kW
2/21/94	40-minute Block No. 2	205 kW
2/22/94	Islanding No. 1	Battery 100 kW, load bank 20–200 kW 108 kW matching tests
2/23/94	Islanding No. 2	Matching 100 kW, varied VARs ± 50 kVAR 208 kW matching 0 kVAR producing vs. consuming Reclose tests
2/23/94	Speed and Stability	Response from SCADA and PCS to mode changes DC injection problems
2/24/94	2-hour load follow No. 1 (equivalent)	Two humped equivalent to a single 2-hour sine
2/24/94	Module harmonics test	Harmonics from 8-1 operating modules planned Unable to run less than four at a time Sensitive to particular module on
2/25/94	3-hour load follow	96-kW peak
2/28/94	2-hour load follow No. 2	134.3-kW peak
3/1/94	4-hour load follow	75.5-kW peak
3/2/94	5-hour load follow No. 1	62.1-kW peak
3/7/94	8-hour load follow No. 1	Cancelled midstream for bad SOC calculations
3/7/94	5-hour load follow No. 2	62.1-kW Ran with corrected SOC calculation Immediately followed the failed 8-hour attempt
3/8/94	Opportunity charge No. 1	2-hour load follow discharge to 25% 2-hour sine charge 2-hour load follow Shutdown early on SOC
3/14/94	8-hour load follow No. 2	38-kW peak
3/15/94	Opportunity Charge No. 2	Different charge/discharge thresholds 2-hour load follow? Deep charge load follow/problems accepting >265 kW 1.5-hour discharge

Date	Test Title	Comments
3/15/94	Container power tests	Discrepancies between requested, commanded, DAS, and PQ node measurements recorded.
3/21/94	250-kW block discharge	Approx. 26-minute test to 25% SOC Modules out on low Vdc (voltage).

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